STUDY OF THE NEUTRONS PRODUCED BY DEUTERON BOMBARDMENT OF Li^7 USING THE PHOTOGRAPHIC EMULSION METHOD.

A Thesis

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CONTENTS

I. INTRODUCTION AND HISTORICAL REVIEW

I.1. Introduction.

Be^8 has not been found as a natural constituent of the earth's crust. According to Bleakney et al. (1936) who examined the mass spectrum, the isotope Be^8 is not present in natural beryllium to a relative abundance greater than 10^{-4}. The nucleus Be^8 can however be formed in some transmutation processes. Its mass is just larger than that of two alpha-particles, the difference being of the order of a hundred thousand electron volts. For this value, the theoretical estimates (Bethe, 1937) give the order of magnitude of the lifetime of a Be^8 nucleus as 10^{-15} to 10^{-17} second. Be^8 should therefore break up spontaneously into two alpha-particles. The information about it, is therefore sought indirectly by analysing the nuclei formed along with Be^8 in some nuclear reactions.

The reaction

$$Li^7 + D^2 \longrightarrow Be^8 + n^1$$

which takes place under the deuteron bombardment of Li^7, is of considerable interest since a study of the energy distribution of the neutrons emitted yields information about the energy level scheme of the product nucleus Be^8.

In the study of energy levels of nuclei one is essentially concerned with locating the various stationary and quasistationary states characteristic of nuclear systems and determining the properties of these states.

Since many arrangements of the nuclear constituents are possible, the stationary energy levels may be pictured as representing those arrangements which are particularly preferred. These may exist for periods of time much longer than that required for a nucleon to traverse the effective dimensions of the nucleus.

With the knowledge in hand regarding well established energy levels, efforts could be successfully made to analyse and explain the events observed. Some simplifying assumptions could be tried. For instance, from time to time the suggestion has been put forward that the alpha-particle configuration or groups of such configurations be regarded essentially as inactive, in a moderately excited nucleus. That would leave only one or two active particles whose interactions need be considered in order to interpret the observed data.

It can be determined only by experiments how far any simplifying assumption is justified. But first of all reasonably complete and reliable information about the energy levels in the nuclei must be available.

In the case of the Be^8 nucleus there is, at present, considerable disagreement regarding its energy levels.

II.2. The $Li^7 + D^2$ reaction.

When Li^7 is bombarded with deuterons besides the reaction in which Be^8 results, a neutron being emitted, there are other modes of disintegration as well. The various ways in which the reaction can proceed are as

follows:

$$Li^7 + D^2 \longrightarrow Be^8 + n^1 \qquad (1)$$

$$Be^8 \longrightarrow 2He^4 \qquad (1a)$$

$$Li^7 + D^2 \longrightarrow Be^{8*} + n^1 \qquad (2)$$

$$Be^{8*} \longrightarrow 2He^4 \qquad (2a)$$

$$Be^{8*} \longrightarrow Be^{8**} + h\nu \longrightarrow Be^8 + h\nu' + h\nu \qquad (2b)$$

$$Be^{8*} \longrightarrow Be^8 + h\nu \qquad (2c)$$

$$Li^7 + D^2 \longrightarrow He^4 + He^4 + n^1 \qquad (3)$$

$$Li^7 + D^2 \longrightarrow He^5 + He^4 \qquad (4)$$

$$He^5 \longrightarrow He^4 + n^1 \qquad (4a)$$

In (1), $Li^7 + D^2$ results in the formation of Be^8 in the normal state which, as has been experimentally found, breaks up into two alpha-particles according to (1a). Be^8 can also be formed in various excited states according to (2). That the Be^8 nucleus is in an excited state is denoted by the asterisk. Be^{8*} can behave in either of the three ways depending on the level of excitation and the angular momentum and/or parity of the level (see sec. IX). It can either disintegrate straightaway into two alpha-particles according to (2a), or after de-excitation to the ground state (2c) or to any other level of lower excitation according to (2b), the latter again behaving in either of the modes (2a) or (2c).

The disintegration can take place through another channel, resulting in two alpha-particles, a neutron being emitted. This can be a single stage three particle break up according to (3) or take place in two stages,

He^5 formed in the first stage breaking up subsequently into an alpha-particle and a neutron. According to Bethe (1937) a break up into three particles in a single process seems very improbable.

Processes (1), (2) and (4) will give rise to homogeneous groups in the neutron spectrum. On the other hand the disintegration process (3) which involves a three particle break up will give a continuous distribution of energies. No substantial evidence exists for reaction (3).

I.3. Summary of studies on $Li^7 + D^2$ reaction.

The neutron spectrum from the Li^7 (d,n)Be^8 reaction has been investigated by several observers, and as in the case of other reactions leading to the same final nucleus, contradictory conclusions have been reached. In the study of nuclear reactions broadly two approaches can be made. In one, use is made of Wilson cloud-chamber or photographic emulsions, where a permanent record of the tracks of the particles may be obtained. In the other approach, the particles are detected by electronic apparatus.

Before the advent of the magnetic spectrometer all the information on particle groups depended on the measurements of range or ionisation, and uncertainties, depending on the method used, affected the results. With the development of the magnetic spectrometer, it is now possible to improve the precision of the results. It can be used to carry out the analysis of γ-radiation with great accuracy. The method of magnetic analysis can

not however be applied directly to neutron spectra. Except for the measurement of the energy of the recoil nucleus from which the neutron has been emitted, which has been carried out in one or two cases, the information on neutron energies has to be obtained from range measurements on proton recoils. The most useful detector for the purpose is the photographic emulsion. By taking observations on a large number of carefully selected tracks, it is possible to obtain higher resolution than could be obtained by cloud-chamber methods.

The lithium d-n reaction was first studied by Bonner and Brubaker (1935) using a methane-filled high pressure cloud chamber. By measuring the ranges of recoil protons in a direction at right angles to the deuteron beam, they found a rather inhomgeneous distribution except for a group near 13 Mev which was interpreted as being due to the transformation of Li^7 into Be^8 and a neutron. The three particle disintegration (3) seemed to account for 95 per cent of the disintegrations.

A similar method was used by Stephens (1938), who measured α-recoil tracks in a helium-filled high pressure cloud chamber. Two distinct groups of neutrons were found, one of which was attributed to the formation of Be^8 in a normal state and the other to the formation of Be^8 in an excited state of about 3.3 Mev. Beyond these groups a more or less continuous distribution was observed which extended to the lowest limit of observation. In later

work Staub and Stephens (1939) reported a plateau in the low energy neutron disintegration which they attributed to the two-stage disintegration,

$$Li^7 + H^2 \longrightarrow He^5 + He^4 \qquad (4)$$

$$He^5 \longrightarrow He^4 + n^1 \qquad (4a)$$

The data of Staub and Stephens above 8 Mev were uncertain since the neutron-helium cross-section was not known accurately for this region.

Richards (1941) studied the energy spectrum of the neutrons from Li + H^2 by the photographic emulsion technique. Tracks were measured in a 100 micron thick emulsion plate placed at 90^o to the 1200 Kev deuteron beam. As for a finite thickness of emulsion, for a given angle of scattering of the recoil proton, the shorter tracks have a greater probability of ending within the emulsion than the long ones, Richards applied a correction to get the correct relative number of short and long tracks, This correction factor varied from 1 to 8 for the energy range 0 to 14.5 Mev. Neutrons of up to 3.5 Mev energy were considered to be produced from the disintegration of Li^6 isotope. Homogeneous neutron groups at 14 Mev and 10.8 Mev were identified to be similar to those reported by Stephens (1938). Richards also reported two higher levels in Be^8 at 7.5 Mev and 10 Mev, the latter being only partially resolved. The data showed no plateau in the region 0.8 - 3.9 Mev which had been ascribed to the neutrons from the two stage disintegration (4).

Results in general agreement with those of Richards were obtained by Green and Gibson (1949). Ilford C2 Nuclear Research plates with emulsion thicknesses ranging from 100 microns to 300 microns were irradiated with neutrons emitted from a thick lithium hydroxide target under bombardment by deuterons of mean energy 930 Kev. Following the method given by Gibson and Livesey (1948) a correction was applied for the tracks which escaped from the surfaces of the emulsion. The correction factor depends on the neutron energy, the emulsion thickness and the maximum scattering angle for which tracks are recorded. It is an approximate correction (see sec. IV.3). Green and Gibson suggested energy levels in Be^8 at 2.8, 4.05, 4.9 and 7.5 Mev.

A detailed study of $Li^7 + H^2$ reaction has been published by Trumpy et al. (1952,1953). Ilford C2 NR 200 μ plates were irradiated at seven angles to the deuteron beam. The observed "energy-number of tracks" histogram was corrected for the escape of tracks from the emulsion. Trumpy et al. suggested a new level in Be^8 at about 2.3 Mev. and confirmed levels at 2.9, 4.1, 4.9 and 7.6 Mev as reported by earlier investigators. In their neutron spectra the peak corresponding to the level near 3 Mev was very broad. The authors have pointed out the possibility that it may include two levels, the second one having an energy value between 3.1 Mev and 3.5 Mev. Their evidence for such a level is not conclusive.

Gibson and Prowse (1955) analysed the neutrons emitted

from this reaction at an angle of 120° to the deuteron beam. They reported groups at excitation energies of 0, 2.1, 2.9, 4.05, and 5.25 Mev. They corrected the observed distribution of neutron energies for the loss to the surface of the 400 μ thick emulsions (Gibson and Livesey, 1948).

Ihsan (1955) using nuclear emulsions found no evidence for levels below 10 Mev excitation other than the 3 Mev. and the 7.5 Mev states. No mention has been made of tracks escaping from the plates.

Catala et al. (1953) claim to have resolved levels in Be^8 at 1.5, 2.2, 2.9, 3.4, 4.1, 5.3, and 7.5 Mev. The technique employed was similar to that used by Richards (1941) and Green and Gibson (1949). As emulsions were only 100 μ thick a large number of tracks escaped from the surfaces of the emulsion. The correction factor for such tracks was obtained from the relation given by Gibson and Livesey (1948), except for energies below 7.5 Mev where a graphical method had to be used.

Bird and Spear (1955) also studied the $Li^7 + H^2$ reaction. In their experimental arrangement, a thin target of separated Li^7 was bombarded by 920 Kev deuterons and the neutrons were detected with 400 μ thick Ilford C2 emulsions, the plates being placed at 90° and 45°, respectively, to the direction of the deuteron beam. The correction for loss of tracks from the emulsion was applied. The results were similar to those published by

Trumpy et al. (1953) and there was no indication of the fine structure reported by Catala et al. (1953).

Trail and Johnson (1954) using a neutron spectrometer studied this reaction and reported only the well known 3 Mev level. Neutron groups leaving Be^8 in an excitation of 4 Mev or 5 Mev would have been resolved if they were ten per cent as intense as the group leaving Be^8 in the ground state. A group leaving Be^8 with an excitation of 7.5 Mev would have been observed if it were twenty per cent of the ground state group. Another neutron spectrometer experiment by Reid (1954) produces evidence for a 5.4 Mev level in Be^8.

I.4. Evidence on energy levels in Be^8 from other processes.

Information on the energy levels in Be^8 has also been obtained by studying reactions other than $Li^7(d,n)Be^8$. A summary of the results is tabulated in Table I along with the reaction studied and the method used.

It is noticed that in the post-1952 experiments only those of Inall and Boyle (1953), Cuer et al. (1954) and Erdos et al. (1953) report levels in Be^8 below 10 Mev excitation, other than the ground state and the 2.9 Mev level. Latest work shows evidence only for the ground and first excited states in this region.

The scattering of alpha-particles in helium also throws light on the even spin, even parity states in Be^8, particularly on the low lying levels. For such a

Table I

Worker	Reaction Studied	Levels in Be^8	Method
Moak and Wisseman (1956)	$Li^6(He^3,p)Be^8$	G.S.,2.9,12.3 Mev.	Sc.Spect.
Inall and Boyle (1953)	$Li^7(p,\gamma)Be^8(\alpha)He^4$	2.9,4.09,5.3,7.5 Mev.	Sc.Count.
La Vier et al. (1956)	" "	2.9,10 Mev	Mag.Spect.
Gilbert (1954)	$Li^8(\beta)Be^8(\alpha)He^4$	2.9 Mev.	Ph.Pl.
Frost and Hanna (1955)	" "	2.9 Mev.	Mag.Spect.
Gelinas and Hanna(1953,1956)	$Be^9(d,t)Be^8$	G.S.,2.9 Mev	Mag.Spect.
Jung and Cuer (1956)	"	2.9 Mev.	Ph.Pl.
Treacy (1953)	$B^{10}(d,\alpha)Be^8$	G.S.,2.9 Mev.	Ion.Ch.
Cuer et al. (1954)	"	G.S.,2.9,4.9,7.2 Mev.	Ph.Pl.
Holland et al. (1955)	"	G.S.,2.9 Mev.	Mag.Spect.
Bockelman and Leveque(1956)	"	G.S.,2.9 Mev.	Mag.Spect.
Brinkworth and Titterton(1951)	$B^{10}(\gamma,d)Be^{8*}(\alpha)He^4$	2.9,4.0,7.5,9.8 Mev.	Ph.Pl.
Erdos et al. (1953)	$B^{10}(\gamma,d)Be^{8*}(\alpha)He^4$	G.S.,2.2,2.9,3.4, 4.0,4.9,6.8 Mev.	Ph.Pl.
Calcraft and Titterton(1951)	$B^{11}(\gamma,t)Be^{8*}(\alpha)He^4$	2.9,4.0 Mev.	Ph.Pl.
Malm and Inglis (1953)	$B^{11}(p,\alpha)Be^8$	G.S.,2.9 Mev.	Mag. Spect.
Holland et al(1955)	"	G.S.,2.9 Mev.	Mag.Spect.
Armstrong and Frye (1956)	$B^{11}(n,\alpha)Li^8(\beta)Be^8(2\alpha)$	2.9 Mev	Ph.Pl.

G.S.= Ground state.
Sc.Spect.=Scintillation spectrometer
Sc.Count.=Scintillation counters

Ion.Ch.= Ionisation chamber
Ph.Pl.= Photographic plate
Mag.Spect.= Magnetic Spectrometer

scattering, the classical Coulomb scattering is very small and therefore anomalies in the scattering will be easily noticeable which can be explained in terms of the various states in Be^8, the compound nucleus formed by He^4 and an alpha-particle. Any resonant behaviour will be characteristic of the angular momenta involved. Among the early α-α scattering investigations, Devons (1939) had the better statistics. His results were consistent with the existence of a broad level in Be^8 with an energy of about 3.3 Mev in excess of the ground state. It is only after 1950 that the problem has been investigated over a greater range of α-particle energies.

Steigert and Sampson (1953) determined the differential scattering cross-section of α-particles in helium, as a function of energy in the range 12.88 to 21.62 Mev, using nuclear emulsions as detectors. They carried out the phase-shift analysis of this data and have reported an S state at 7.55 Mev and a G state at about 10.8 Mev in the compound nucleus Be^8.

Similar experiments have been performed by Nilson et al. (1956) in the α-particle energy range 12.3 to 22.9 Mev. Below 21.65 Mev alpha-energy, using nuclear emulsions as the detectors, the procedure was entirely identical to that of Steigert and Sampson (1953). Using a computer for determining the phase-shifts, Nilson et al. (1958) analysed their own data along with the low energy scattering data of the Carnegie Institution and of the Rice Institute

and have reported only three states in Be^8 below 12 Mev excitation with even spin and parity, the S-, D- and G wave phase-shifts indicating respectively the ground state, the 2.9 Mev state and a state in the neighbourhood of 11 Mev. The existence of a 0^+ 7.5 Mev state is clearly excluded. Accuracy of the analysis favours Nilson's results as compared to Steigert and Sampson's.

I.5. The γ - ray spectrum.

The evidence for excited states in nuclei is also obtained from the γ - rays emitted by the residual nucleus. The formation of Be^8 in various excited states may possibly result in the emission of gamma-rays as a secondary process.

Williams et al. (1937) reported a gamma-ray of energy 400± 25 Kev from the disintegration of ordinary lithium by deuterons. This γ-ray was ascribed to the return of excited Li^7 nucleus to its normal state according to the following mode of disintegration:

$$Li^6 + H^2 \longrightarrow Li^{7*} + H^1$$

$$Li^{7*} \longrightarrow Li^7 + h\nu$$

Such a γ-ray was not observed by Bennett et al. (1941, 1947) who studied the same reaction, again using Geiger Counters.

A thick graphite absorber was used between the target and the counters to stop the beta-rays from Li^8. Bennett et al. have reported a 4.9 Mev gamma-ray and taken it as

evidence of an excited state in Be^8 which emits a γ-ray before breaking up into two alpha-particles.

Recently a systematic study of γ- rays from five nuclear reactions has been made by Sinclair (1954). In the case of bombardment of lithium by 650 Kev deuterons an absorber of thickness just sufficient to stop the Li^8 beta-rays, was interposed. All parts of the system struck by the beam were carefully cleaned of carbon and other deposits to reduce spurious sources of gamma radiation. No indication was found of gamma-radiations between widely separated states of Be^8. Upper limit for the cross-section has been set at 2 mb for the production of 5 Mev gamma rays. The 4.9 Mev gamma radiation reported by Bennett et al.(1947) has been explained to be due to 4.47 Mev γ-ray from C^{12*}, produced by the inelastic scattering of neutrons in the thick graphite absorber which was used.

Similar results had also been obtained earlier by Lauritsen and Crane (1934) who were satisfied from intensity considerations that γ-rays observed from lithium targets arose from hydrogen impurity of the deuteron beam and not in disintegration by deuterons.

From these results it can be concluded that the excitation energies, angular momenta and parity of the energy levels of Be^8, lying in the region investigated, are such as to allow only particle disintegrations.

I.6. The energy levels in Be^8.

The information available on the various states in Be^8 can be summarised as follows:

a). The ground state.

It was first shown by Kirchner and his collaborators (1937) that a normal Be^8 nucleus disintegrates into two alpha-particles before it has lost an appreciable amount of energy by ionisation. This was later confirmed by Laaf (1938) and Fink (1939), who from their experiments put the energy of disintegration in the range 100 to 200 Kev. Wheeler (1941) obtained the most satisfactory representation of their observations with an energy of disintegration of 125± 25 Kev.

Post 1947 results for the disintegration energy of Be^8 in the ground state are summarised in Table 2.

Table 2

Worker	Reaction studied	Q(in Kev)	Method
Hemmendinger (1949)	$Be^9(\gamma,n)Be^8$	103±10	P.Ht. expts.
Tollestrup et al. (1949)	$Be^9(p,d)Be^8$	89±5	Mag. Spect.
Crussard (1950)	Cosmic Ray stars	85±10	Ph. Pl.
Jones et al. (1953)	$B^{11}(p,\alpha)Be^8$	94±1.4	Elect. Spect.

P. Ht. expts. = Pulse-height experiments.
Elect. Spect. = Electrostatic spectrometer.

The weighted mean of all these measurements is 94± 1.3 Kev (Van Patter and Whaling: 1954).

For this value theoretical estimates (Bethe, 1937) give the order of magnitude of the lifetime of a Be^8 nucleus as 10^{-15} to 10^{-17} second. The principle of uncertainty correlates with the lifetime an indeterminacy in energy or a natural width (width at half maximum) of 1 ev to 100 ev, which is far too small to be significant in any experiment.

The break up of Be^8 into two α-particles gives a final system composed only of two identical particles. The spin of an alpha-particle is zero and its internal wave function has even parity. As α-particles have Bose-Einstein statistics, the wave-function describing the relative motion of their centre of gravity must also have even parity and must have only even orbital momenta. Thus the wave-function of the final system containing two α-particles must have even parity and even total angular momentum. Due to conservation of angular momentum, any level in Be^8 which can break up into two α- particles must also have even angular momentum. Parity conservation requires that the level must have even parity as well.

The assignment $J = 0^+$ has been made to this state, (Ajzenberg and Lauritsen, 1955).

b). The first excited state.

All experimental data give a level in Be^8 with an excitation of 2.9 Mev above the ground state. Some

investigators, as summarised earlier (see sec. I.3. and I.4.), have brought forth evidence of a fine structure in the first excited state and have reported levels at 1.5, 2.1, 4.0 and 4.9 Mev besides the one at 2.9 Mev. Other workers have observed only a broad level at 2.9 Mev.

If the existence of a level at $\sim$ 2.1 Mev is accepted, the width of the 2.9 Mev comes to $\sim$ 0.8 Mev, according to Gibson and Prowse (1955). This value gives the order of magnitude of the lifetime of this state as 10^{-21} second.

This level is capable of breaking up into two alpha-particles and must therefore have an even orbital momentum and even parity. It has been established that it is a $J = 2^+$ level (Ajzenberg and Lauritsen, 1955).

c). The other levels.

Although levels have been reported in Be^8 at $\sim$7.5, 10 and 14.7 Mev little information is as yet available about them. As a matter of fact these states can not at present be regarded as well established.

I.7. Outline of the present work.

At the time this investigation was begun the available information on the energy levels in Be^8 showed a considerable lack of agreement, particularly in the region of the first excited state. From nearly all experiments in which photographic plates were used, other levels beside the 2.9 Mev one had been reported. Other techniques, which also had good statistics, denied the existence of any

level below 10 Mev excitation other than the ground and 2.9 Mev states.

In view of this conflicting evidence it was thought that a further systematic study of the energy levels in Be^8, using the nuclear emulsion method, would be profitable. It was felt that, since the experimental technique used by Catala et al. (1953) was similar to that used in other photographic plate experiments, their suggestion of a fine level structure needed confirmation.

To eliminate the contribution of the $Li^6(d,n)Be^7$ reaction which takes place on deuteron bombardment of ordinary lithium, it was decided to use a separated Li^7 isotope target. This would make possible the interpretation of the lower energy end of the neutron spectrum.

The possibility of reducing the number of recoil proton tracks that escaped from the surfaces of the emulsion was also considered. The procedure for scanning the plates was therefore modified. (see sec. IV.1. and IV.3.).

When the measurements of ranges of two thousand recoil protons, in the plate held at 0° to the direction of the deuteron beam, had been completed, it was found that nearly two-thirds of the protons had energies of less than 5 Mev and only the remaining were recoils from neutrons with energies that corresponded to the formation of Be^8 in the ground and first excited states. Similarly out of a thousand tracks measured on the 135° plate, it was

found only about one-fourth had energies greater than 4 Mev. As the region of special interest lay about the first excited state in Be^8, it was decided to improve the statistics in that region. Consequently a lower limit for the lengths of the tracks was set for further measurements. For the 135° plate only those tracks whose lengths exceeded 100 microns were considered during the second series of measurements. The range of 100 microns corresponded to a Q value of 3.96 Mev for the $Li^7 + D^2$ reaction. The proton ranges corresponding to this Q value were determined at the other angles of observation (see sec. IV.1.) and only those tracks whose lengths exceeded this limiting value were considered for measurement. Under this additional criterion, 817 proton tracks were measured at each of the four angles of observation.

Measurements for the low neutron energy side of the spectrum have thus been made only at angles of 0° and 135° with respect to the deuteron beam. These results have been reported separately in sec. XI .

II EXPERIMENTAL PROCEDURE

II.1. The neutron source.

The separated Li^7 isotope target was obtained from the Atomic Energy Research Establishment, Harwell. It had a 220 μ gm./cm.^{2} loading on 0.005 in. copper backing.

In the preliminary runs the target was bombarded with the deuterons accelerated by the 1.2 Mev Cockroft-Walton generator of the University of Edinburgh. The generator itself is of standard design, built and installed by Philips, Ltd., and though the maximum voltage is nominally 1 Mev, it was difficult to go much beyond 650 Kev. The ion source is of the Oliphant type, a simple discharge tube which has given a maximum total beam current, when running on deuterium, of about 25 μ amperes. The beam of deuterons is accelerated vertically through a system of focusing electrodes into the target chamber, where it is analysed into its separate components by a large electromagnet whose field strength is such as to pass the deuteron beam along a side tube at 30° to the vertical. The target itself on the copper backing fits into the target holder, which is soldered to the cooling duct through which a continuous flow of cold water is passed while bombardment is taking place.

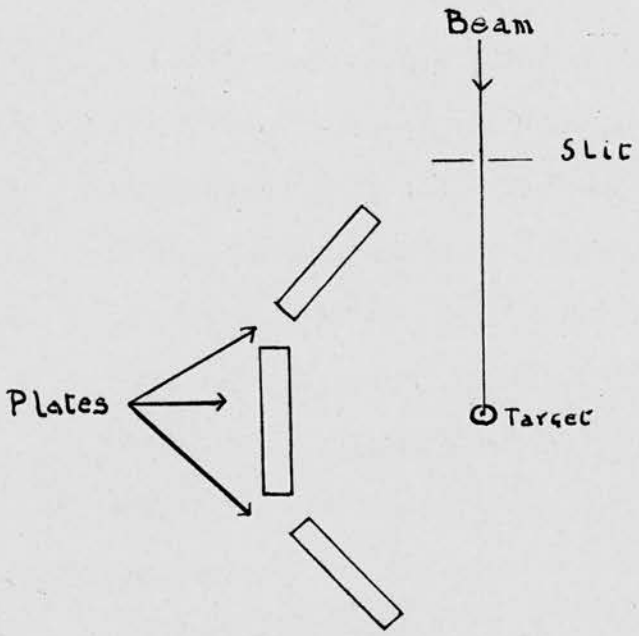
The photographic plates irradiated using the Edinburgh H.T. set were found to be unsatisfactory on

being processed (see sec. III.2.). As a new ion source was being installed another exposure on this machine was not possible. An exposure was therefore arranged for at the Department of Natural Philosophy, University of Glasgow. The Glasgow H.T. set is identical to the Edinburgh machine. It provided a deuteron beam of energy 635 Kev, the maximum fluctuations being ~5 Kev. The maximum resolved beam current was 26 μ amperes. The total deuteron charge on the target was 250 μ ampere-hours which gave a suitable density of proton tracks in the photographic emulsions.

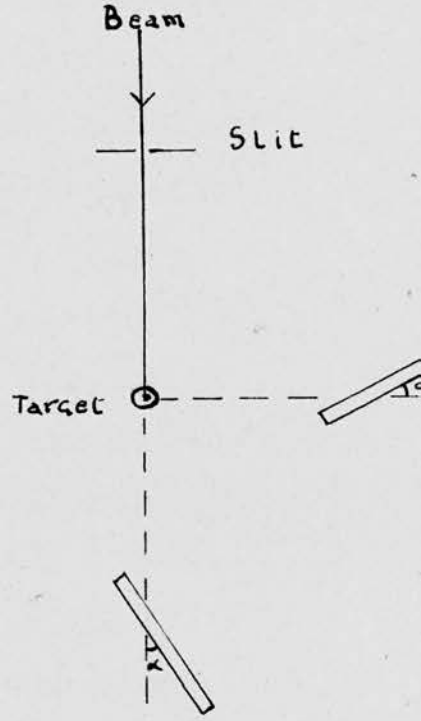
II.2. Exposure of the plates.

For solid targets with which the reaction products of a nuclear process are to be investigated, plates may be placed tangentially and partially surrounding the target at an appropriate angle with the horizontal so that identifiable tracks are produced. An arrangement of this type (see fig. 1a) was used by Talbott et al. (1950) in determining the distribution of alpha-particles from the disintegration of Li^7 by protons. The known geometry of the plates during the exposure enables the conversion of the position of every track in the emulsion to its corresponding angle of emission.

Another arrangement with plates distributed radially around a target was used by Wilkins (1940). In this



(a)



(b)

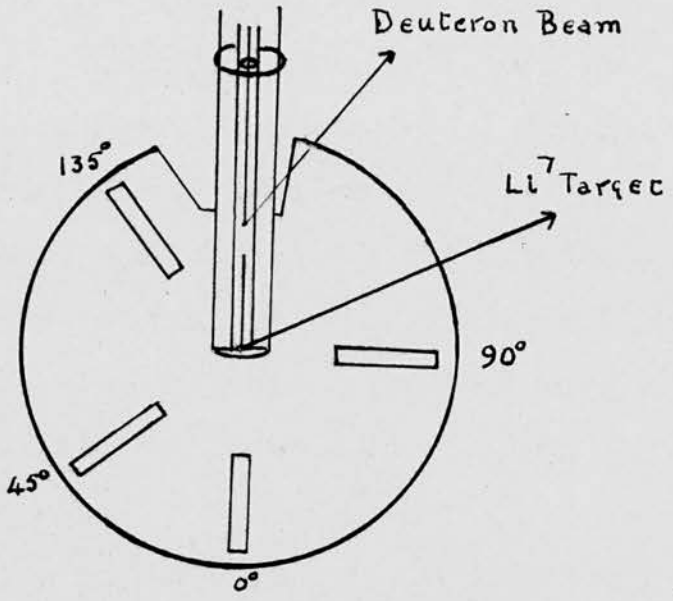
FIG.1. IRRADIATION GEOMETRY

(a) Tangential arrangement.
(b) Radial arrangement.

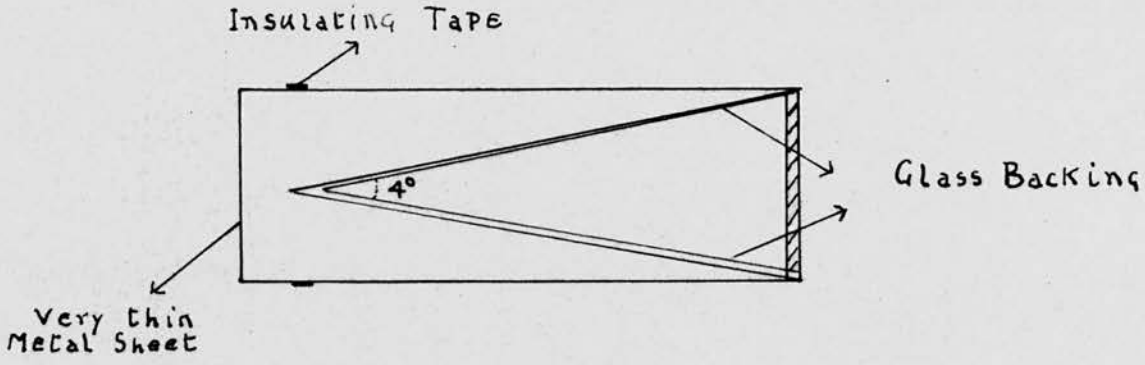
case the particles were incident on the edges of a large number of plates, each plate providing information on a specific scattering angle. The angle α (see fig. 1b) is a matter of experimental convenience.

For the present work the latter arrangement was preferred. Ilford G5 Nuclear Research plates (3 ins. by 1 in.) with an emulsion thickness of 400 microns were placed radially at a distance of 17.3 cm. from the target at different angles to the deuteron beam and were irradiated simultaneously. The plates were taken from the same batch in the hope that the emulsion had the same composition in each; it will have the same shrinking factor (see sec. IV.2.) and obey the same range-energy relation as far as possible.

The experimental arrangement is shown in fig. 2 a. The plates were enclosed in light-tight boxes made of thin metal sheet. Each box held two plates, placed glass to glass at an angle of 4° to one another as shown in fig. 2 b. The boxes were clamped in position near the target by metal strips, on to a circular metal disc graduated at 5° intervals. At the desired positions (in this case at angles of 0°, 45°, 90° and 135° to the direction of the deuteron beam) a box was placed with both of its end-faces, towards and away from the target, aligned to the angle defining line on the disc. Making observations on two inclined plates for any particular angle would correct for any possible error in alignment.



(a)



(b)

FIG.2. EXPERIMENTAL ARRANGEMENT.

The 4° angle of inclination between plates enclosed in each box was taken into account while scanning the plates.

III THE NUCLEAR EMULSION TECHNIQUE

III.1. Introduction.

Special photographic emulsions have been developed for the study of ionising particles produced in nuclear reactions, nuclear fission and nuclear disintegrations.

The photographic plate was first used as a detector of individual nuclear particles by Kinoshita at Manchester. In 1927, Blau and Wambacher managed to record tracks of fast protons, using thick emulsions. Up to 1939 the emulsion technique was considered to be only a qualitative method. This situation changed when Powell after performing a series of experiments showed that the energy of a particle can be accurately obtained from the length of its track in the emulsion. The full value of the technique became evident when after the war, emulsions were developed which offered a whole range of sensitivities. Since 1948, Kodak have produced the NT4 emulsion and Ilford the G5 emulsion which possess high sensitivity and are therefore capable of recording tracks at minimum ionisation energies.

The emulsions now used contain silver bromide to the extent of 80% or more of the dry weight, this being about ten times the quantity present in plates or films used for normal photographic purposes. An ionising particle travelling through the emulsion of a photographic plate leaves a track containing a number of developable silver

bromide grains which on being processed are reduced to black specks of silver. The path of the particle thus appears as a line of developed grains. The more strongly ionising the particles the more numerous are these grains; and the greater their initial energies, the longer the resulting tracks. From these quantities the particle can be identified and its energy determined.

Neutrons do not ionise directly when passing through matter and so they are detected indirectly by noticing the ionisation caused by secondary particles, the latter may be recoils projected by elastic impacts of neutrons on nuclei.

The process of formation of a latent (i.e. developable) image along the path of an ionising particle in a nuclear emulsion is essentially similar to that which occurs in an ordinary light sensitive photographic emulsion. Only the mechanism of ion pair formation is different: in the former this takes place through the electrostatic interaction between the charged particle and the electrons of the emulsion atoms, and in the latter case, by the photo-electric emission of electrons by incident photons.

After being developed the emulsion contains, besides the reduced silver metal forming the image of the path of the ionised particle, the residual silver halide unaffected by the developer. The fixing process dissolves out the halide, leaving the developed grains

embedded in the gelatin. Washing with water removes the fixing salts from inside the emulsion.

III,2. Processing of the plates.

After being irradiated, the plates were developed following essentially the method of Dilworth, Occhialini and Payne (1948). This method known as the "Temperature development" ensures uniform development as the developer has time to permeate the emulsion before it acts. This is achieved by soaking the plates in ice cold developer. As the rate of development has a higher temperature coefficient than the rate of permeation, the developer only seeps through the emulsion and no development takes place in the chilled bath. The temperature is then raised for a suitable period depending on the nature of the plates being processed.

The following developer was used:

Sodium sulphite (anhydrous)	18 gms.
Potassium bromide (10% solution). . .	8 c.c.
Amidol.	4.5 gms.
Distilled water up to	1000 c.c.

Stop-bath:

Sodium bisulphite	5 gms.
Distilled water	100 c.c.

Fixing bath:

Sodium thiosulphate	500 gms.
Distilled water	1000 c.c.

The plates were first soaked in water for about an hour. The developer was put in a dish and cooled in ice. The plates were put in the cold developer for about 100

minutes. They were then transferred to a "warm-bath" (temperature 19°c.) and left there for 30 minutes, so that "dry development" took place. The developed plates were next put in the stop-bath for about 45 minutes. If the plates at this stage had an opaque layer of silver on their surfaces, this was rubbed off gently with a finger tip before putting the plates in the fixer. After about 24 hours one of the plates was taken out of the fixing bath to find out whether the fixing process was complete, in which case the plate should be more or less transparent when looked at against the red light. Usually it took about three to four days for the fixing. The fixing bath was then diluted, gradually at first, with a stream of tap water. The washing of the plates was discontinued when a sample of wash-water showed no trace of residual hypo (a drop of dilute potassium-permanganate solution is decolourised when dropped into water containing a trace of hypo).

The plates were taken out of the water and left to dry. When dry they were put in a glycerine bath (3 gms. of glycerine in 100 c.c. of water). If this is not done the emulsion has a tendency to become brittle and is likely to come off the glass. After about six hours the plates were taken out, their surfaces mopped gently with a filter paper and then left to dry.

It was found that the Ilford C2 emulsion was affected to a great extent by the temperature of the "warm bath"

and during development, at a temperature of about 25°c, tended to go so soft that the emulsion started peeling off the glass. While such plates were in the fixing bath, Kodak hardner was added in the proportion mentioned by the manufacturers (7.5c.c. of hardner to 100 c.c. of fixer). The emulsion became so hard that the hypo solution could not permeate the surface of the emulsion and the plates could not be properly fixed. On completion of processing, observation of these plates under the microscope showed considerable distortion of tracks. This might have been introduced by the rapid and uneven action of the hardner. Extreme caution is therefore suggested if any hardner is to be used during processing. If possible in such cases a lower temperature should be tried for the development.

The Ilford G5 emulsion was found completely satisfactory and all the measurements in the present work have been carried out on the tracks in G5 emulsions.

IV MICROSCOPIC EXAMINATION

IV.1. The measurement of ranges of recoil protons.

The plates were examined on a Cooke, Troughton and Simms microscope No. M.40174 specially built for nuclear research. It is provided with different combinations of objectives and eyepieces. For scanning the plates an oil immersion objective was used along with a x15 eyepiece, which gave an overall magnification of 675. A 2.2 m.m. oil-immersion objective having a magnification of 80 was used along with the x15 eyepiece for all the measurements.

The stage is designed so that measurements may be made over slides 75 m.m. x 25 m.m. It has motions at right angles to one another with the help of two micrometres, each having a range of 25 m.m. As it is possible to read these micrometres up to 0.5μ, the observed scale readings are accurate to within 1μ. Taking the X direction to be along the length of the plate and the Y direction along the width, the readings on the two micrometres give the X and Y components of the track length projected on the emulsion plane.

The depth measurements are made in terms of arbitrary scale divisions, the equivalent value of which in microns is then deduced (see sec. IV.2.). The value of one scale division varied from about 1.5 to 2.0μ during the course of the work. This scale could be accurately read up to half a scale division and the consequent error introduced in the observed thickness of

the emulsion was less than 0.25%.

Knowing the three components r_x, r_y and r_z of the actual track length along the three axes X, Y and Z respectively, at right angles to one another, the range R of the particle could be calculated from the relation

$$R^2 = r_x^2 + r_y^2 + r_z^2$$

The scanning of the plates was carried out in 24 m.m. long traverses. On the eyepiece graticule a square was marked with sides corresponding to each 101μ in length. Only those tracks that originated within the area of this square were considered.

As the thickness of the emulsion varies with the humidity it was [redacted] measured, several times daily during the period measurements were in progress. Changes in thickness of about 5 divisions of the depth scale ($\sim 10\mu$) were sometimes noticed within a few hours.

The whole body of the emulsion was not scanned. Emulsion thicknesses equivalent to 30 and 80 divisions of the depth scale, respectively, were left out at the top and bottom surfaces of the plate. The layer lying in between these limits was searched.

The volume of emulsion scanned, V, is given by

$$V = b.X.\ (d-110)\ \frac{400}{d}\ \text{micron}^3$$

$$= 101.X\ (d-110)\ \frac{400}{d}\ \text{micron}^3$$

where, d = the total thickness of the emulsion in arbitrary divisions of the depth scale,

X = length of the traverse along the X-direction,
b = width of the traverse = 101 microns

To obtain the total volume of the emulsion searched, values of V were integrated over the different values of X and d. This was later used to deduce the number of tracks obtained per unit volume which may be called the "yield of the reaction".

Only those tracks that fulfilled the following conditions, were counted:

a) The projection of the track on the emulsion plane had to make an angle $\beta \leq 5^{\circ}$ with the projection of the neutron direction on this plane. During the course of the measurements on any plate the projected neutron direction was taken to be parallel to the length of the plate, the latter serving as the line of reference against which the angles subtended by the tracks in the emulsion plane were measured. Actually it subtends a small angle, a correction for which was later applied (see sec. V.3.)

b) The angle θ between the track and its projection on the emulsion plane had to be $\leq 3^{\circ}$ for the track of a proton travelling towards the surface of the emulsion and be $\leq 7^{\circ}$ for one moving towards the bottom of the plate.

c) The length of the track had to exceed a lower limit (varying from plate to plate).

The difference in the values of θ in condition b) for deciding whether a track is acceptable or not arose due to the 2° angle of inclination of the plates with the neutron direction during irradiation. It can be shown (see appendix I) that the angle α between the track, of a proton coming towards the surface of the emulsion, and the neutron direction is $\theta + 2^{\circ}$. Similarly if the proton travels towards the bottom of the emulsion α is equal to $\theta - 2^{\circ}$. Hence in order to have an angle $\leqslant 5^{\circ}$ between the incident neutron and recoil proton directions, the observed angle θ between the track and the emulsion plane had to be $\leqslant 5^{\circ} + 2^{\circ}$ and $\leqslant 5^{\circ} - 2^{\circ}$, respectively, for protons moving towards the bottom and top surfaces of the emulsion. The angle θ was estimated by measuring the vertical distance between the ends of a straight portion of the track, which distance was then referred to the projected length of the track on the emulsion plane.

As the portion of the neutron spectrum of special interest corresponded to a Q value $\geqslant 3.95$ Mev, there was a lower limit set for the neutron energy. Consequently only those recoil proton tracks whose lengths exceeded a limiting value were measured. This lower limit of the proton ranges R_{min} varied from plate to plate depending on the angle of inclination of the plate to the incident deuteron beam. The values of R_{min} are shown in Table 3 . These values were calculated with the

Table 3

Angle of inclination of the plate	0^{o}	45^{o}	90^{o}	135^{o}
R_{min} in μ	142.8	137.6	117.5	100

help of the equation (see appendix II)

$$E_n^{\frac{1}{2}} = 0.158 \cos\theta\, E_d^{\frac{1}{2}} + [0.888Q + 0.665E_d + 0.025 \cos^2\theta\, E_d]^{\frac{1}{2}}$$

where, E_n = energy of the neutrons

E_d = energy of the deuterons

θ = angle of inclination of the plate to the deuteron beam, all quantities being measured in the laboratory coordinates.

At each of the four angles 817 tracks were measured. All the measurements were carried out by the author so that the personal error in the observations remains the same throughout.

For each track the angle β, in the emulsion plane, at the point of origin of the track was also recorded. For the measurement of the range every track was considered to be made up of a number of straight segments, the length of each of which was individually noted. The sum of the calculated actual lengths of the segments gave the range of the recoil proton.

IV.2. Shrinkage of emulsion

Due to the removal of the unused silver bromide during fixation there occurs a shrinkage of the emulsion

on processing. The nature of the shrinkage was studied by Powell et al. (1946) and Rotblat and Tai (1949). It was found that no appreciable change occurs in the length or width of the emulsion, but there is a 10 to 50% reduction in the emulsion thickness depending on the initial composition. It is therefore necessary to take this into consideration while measuring r_z, the vertical component of the range.

In the investigation of the $Li^7 + D^2$ reaction, Green and Gibson (1949) following the method described by Gibson and Livesey (1948) corrected the vertical distances by multiplying them by a factor S , which was assumed to be equal to the ratio of the pre-and post-processing thicknesses. A series of experimental determinations of the shrinkage factor S for the 100 μ Ilford C2 plates indicated $S = 2 \pm 0.2$ and this value was used in the range measurements. Catala et al (1953) have also obtained the same value of the shrinking factor.

As the thickness of an emulsion changes considerably with the quantity of absorbed moisture (depending on the atmospheric humidity) the value of the shrinkage factor employed will be incorrect since the determination of S and the measurements of the range have been done under different conditions. Even if a correction is made by noting the atmospheric humidities on the respective days, the shrinkage factor so determined is still approximate.

Roads (1951) has found that for Ilford G5 emulsion the shrinkage factor increases with the time of storage in a saturated atmosphere. Frequent determinations of the value of S are therefore necessary.

In the present work the need of determining the shrinkage factor has been done away with, by taking the thickness of the emulsion, obtained in arbitrary scale divisions while measurements of track lengths were being made, to be equivalent to the known thickness of the unprocessed emulsion, 400 μ in this case. The value of each scale division thus deduced, in microns was used for estimating the angle θ and also in calculations of the ranges. With the change in thickness of the emulsion with variation in humidity, the value of a scale division in microns also changed accordingly and no errors entered the range determinations.

IV.3. Escaping of the tracks from the surface of the emulsion.

The highest energy group of particles emitted from the $Li^7 + D^2$ reaction gives rise to recoil protons which have ranges in the emulsion of about 1000 to 1080 μ. Some of the protons do not come to a stop within the emulsion. Consequently a correction is necessary for such tracks whose full range cannot be determined.

Trumpy et al. (1953) used 200 μ thick emulsion plates and counted those tracks for which the angle between the

track and its projection on the emulsion plane was $\leqslant 7.25^{\circ}$. They applied a correction for the protons which escaped from the surfaces of the emulsion. This correction depends on the neutron energy, the thickness of the emulsion and the maximum scattering angle for which the tracks are accepted. A similar correction has been applied by Catala et al.(1953) who also studied the same reaction. Catala's correction factor is larger by about a factor of 2 as compared to Trumpy's, as 100 μ thick emulsions were used together with a larger angle of acceptance namely $\leqslant 19.5^{\circ}$. The factor was obtained from the relation

$$f = 1 - \frac{R_o}{8\pi d} \cdot \frac{\{(\gamma_2 - \gamma_1) + \frac{1}{4}(\sin 2\gamma_2 - \sin 2\gamma_1) - \frac{1}{4}(\sin 4\gamma_2 - \sin 4\gamma_1) - \frac{1}{2}(\sin 6\gamma_2 - \sin 6\gamma_1)\}}{(\sin^2\gamma_2 - \sin^2\gamma_1)}$$

where f is the fraction of the total number of protons scattered in the range $\gamma_1 \leqslant \gamma \leqslant \gamma_2$ which are recorded in an emulsion of thickness 2d. R_o is the range of a proton with energy E_n.

This correction was calculated geometrically by Gibson and Livesey (1948) and is valid provided $R_o \cos^3\gamma_2 \sin\gamma_2 \leqslant 2d$ and the proton range varies with energy according to the Geiger Rule,

$$R = \text{constant } E_p^{1.5}$$

where R is the range for proton of energy Ep; So that $R = R_o \cos^3\gamma$ for a scattering angle γ. As this rule does not accurately represent the range-energy relation

for

for protons, the correction factor is approximate.

Trumpy et al. (1953) give the approximate relation

$$f = 1 - \frac{Ro}{48d} \cdot \frac{1-\cos^6\alpha}{2\alpha + \sin 2\alpha} \cdot \frac{12\beta + 8 \sin 2\beta + \sin 4\beta}{\sin \beta}$$

where R_0 is the range of a recoil proton in the forward direction, β is the angle between the projection of the track on the emulsion plane and the projection of the neutron direction, α is the angle between the track and its projection on the plane of the emulsion and d is the emulsion thickness. Table 4 shows the values of f against neutron energy, as calculated from their data.

Table 4

Neutron energy E (in Mev)	8	10	12	14
f	1.0	0.81	0.77	0.73

It is noticed that in the region of the first excited state of Be^8 about one-fifth and in the region of the ground state about one-fourth of the total number of recoil protons escape from the surfaces of the emulsion.

The number of particles escaping can be reduced by using thicker emulsions and by choosing a smaller angle of scattering for which tracks are accepted. Consequently for the present work 400 μ thick emulsions were used and proton recoil tracks making only an angle $\leqslant 5^\circ$ with the incident neutron direction were recorded. In order to

further reduce the number of tracks lost, the whole thickness of the emulsion was not scanned. By considering only those tracks that originated in the region extending from about 50μ to about 250μ below the surface of the emulsion, the search was limited to about half the thickness of the plate (see sec. IV.1.). Thus, although a larger area of the plate had to be scanned, a greater thickness of emulsion was available to the particles whose tracks started in the observed region. Therefore a greater probability of the recoil particles stopping within the emulsion surfaces, was expected.

The results showed that out of more than 3000 tracks counted only 15 left the emulsion. The number of tracks escaping being 5, 5, 3, and 2 respectively from plates at angles of 0°, 45°, 90° and 135° to the deuteron beam. As these numbers are insignificantly small compared to the number of tracks measured on each plate, no correction is necessary for the tracks leaving the emulsion.

V. DETERMINATION OF ENERGY OF THE NEUTRONS

V.1. The range-energy relation for protons.

To estimate the energy of a charged particle from its observed range in a nuclear emulsion it is necessary to use some range-energy relation. Although the energy loss of such a particle takes place in discrete amounts of energy in random collisions with electrons of the stopping substance, the process may be considered continuous when taken over a finite path length.

The average energy loss per unit distance $\frac{-dE}{dx}$, by collision processes has been given by Livingston and Bethe (1937) from a quantum-mechanical derivation as

$$-\frac{dE}{dx} = \frac{4\pi z^2 e^4 N}{mv^2}\left[Z\left\{\log\left(\frac{2mv^2}{I}\right) - \log(1-\beta^2) - \beta^2\right\} - C_k\right]$$

where ze is the charge of the particle and v its velocity, N the number of atoms per cm^3 of the stopping material, Z and I their atomic number and average ionization potential, respectively, m the electronic mass, $\beta = \frac{v}{c}$, and C_k a correction term required only in the event that v is comparable with K electron velocities of the stopping atoms but large with respect to those of the other orbital electrons. For velocities occurring in nuclear processes ($< \sim 5 \cdot 10^9$ cm. $sec.^{-1}$) the relativistic terms are negligible.

Knowing the specific energy loss $dE/_{dx}$ and the initial energy of an incident particle, the range is given by

$$R = \int_0^E dE/(dE/dx)$$

This integral has been accurately evaluated for protons in air up to energies of 15 Mev by Livingston and Bethe (1937). Tables for ranges in air for the different charged particles have also been given by Holloway and Livingston (1938), Smith (1947), Bethe (1950), and Jesse and Sadauskis (1950).

To obtain the stopping effects of substances other than air, use is made of a term "the differential stopping power of a substance", $\bar{S}$, defined as

$$\bar{S} = \frac{Ra}{R}$$

where R_a and R are the thicknesses of air and of the substance, necessary to reduce the energy of a charged particle by a given small amount. Another quantity is "the differential atomic stopping power", $\bar{s}$, given by

$$\bar{s} = \bar{S} \left(\frac{Na}{N}\right)$$

where N_a and N denote the number of atoms per c.c. of air and the substance, respectively. $\bar{s}$ measures the effectiveness of an atom of the substance in stopping a charged particle, relative to that of an average air atom.

Tables for values of $\bar{s}$ for several elements have been given by Livingston and Bethe (1937), Webb (1948), Hirschfelder and Magee (1948) and Kelly (1949). From these tables following the procedure given by Webb values

of the "differential stopping power", $\bar{S}$, for the different emulsions have been calculated from the knowledge of their atomic compositions. The emulsions were taken to be homogeneous mixtures of the components for this purpose.

With the help of these data for $\bar{S}$, using a range-energy relation for any particular particle in standard air, the "integral stopping power", S, of an emulsion for that particle can be calculated, following the method adopted by Webb. S is defined by

$$S = \frac{Ra}{R}$$

R_a and R being the ranges in air and the emulsion respectively. It is noticed that there are no significant discrepancies between experimental observations and the stopping power calculations mentioned above.

Lattes, Fowler and Cuer (1947) carried out a range-energy caliberation for protons and alpha-particles. They took no precautions to avoid variations in the moisture content of their emulsions and there is a considerable probability of changes in the stopping power due to this cause. In the more recent investigations of ranges of protons and alpha-particles carried out by Rotblat (1950) and for protons by Bradner et al. (1950), although care was taken to eliminate random variations of the emulsion moisture content, no measurements were made on the actual moisture content and therefore there is an

uncertainty in using their range-energy relations.

Two further experimental range-energy calibrations have been given by Rotblat (1951) and by Catala and Gibson (1951). That the correlation between alpha-particle and proton ranges was not considered in either of these experiments and that the discrepancies in this respect, of 1 μ or more at proton energies near about 5 Mev were overlooked has been pointed out by Wilkins (1951).

Wilkins (1951) has measured the change in density of the emulsion with its moisture content and has observed the range of thorium-C' alpha-particles in several emulsions of carefully measured density. There were no significant discrepancies between experimental results and the calculated values.

When 1 c.c. of an emulsion of density ρ_o absorbs w c.c. of water its density changes to ρ, given by

$$\rho = \frac{(\rho_o + w)}{(1 + w)} \text{ gm. per c.c.}$$

ρ_o can be put equal to 4.18 gm. per c.c., this being the value quoted by Ilford, Ltd., for "absolutely dry" emulsion. So that ρ is given by

$$\rho = \frac{(4.18 + w)}{(1 + w)} \text{ gms. per c.c.} \qquad -(5.1)$$

Hence,

$$w = \frac{(4.18 - \rho)}{(\rho - 1)} \text{ c.c.} \qquad -(5.2)$$

Following the procedure given by Wilkins, the density

of the emulsion of the plates irradiated was determined by taking a plate from the same batch and measurements made of the weight, area and thickness of the emulsion plus glass backing, the thickness being noted at several points of the plate. The weight and thickness of the glass backing alone was also recorded. From the relations (5.1) and (5.2) the value of ρ or w was then calculated. The density of the emulsion was later taken into consideration (see sec. VI.6.)

For the present work the range-energy relation for protons, in Ilford C2 plates (emulsion density 3.92 gms. per c.c.), given by Wilkins (1951) was used. According to him the ranges in G5 emulsions exceed the corresponding C2 emulsion ranges by 0.5μ . A table was constructed for the range-energy values for protons in Ilford G5 emulsions, in which besides including the 0.5μ correction factor, the ranges were calculated in 0.1 Mev energy steps by interpolation. The proton ranges provided by Wilkins are in 0.05 to 0.5 Mev energy intervals for energies up to 15 Mev. The interpolated values of the ranges between energies of 3 to 4 Mev had to be smoothed. For this the 21-term Spencer formula (Whittaker [redacted] and Robinson: 1944; p.290) was used.

V.2. The energy histogram.

From the range-energy relation thus obtained, the proton energy corresponding to the measured range in the emulsion was noted. The data for each angle of

observation with respect to the deuteron beam, were arranged in the form of histograms with the number of tracks plotted as ordinate against the energy in 0.1 Mev intervals as abscissa.

The histograms for the four angles of observation 0°, 45°, 90° and 135° are shown in fig. 3.

Each of the histograms shows a high energy group of particles, lying about 13 to 14.5 Mev at the different angles. This group must correspond to the formation of Be^{8} in the ground state. The group is strongest on the 0° plate.

There is a broad group of particles centred at about 10.5 to 11.5 Mev. This appears on all the histograms.

This broad group is followed by a distribution of particles such that their number in an energy interval goes on increasing as the lower energy end of the histogram is approached.

V.3. The energy of the neutrons.

It is the energy of recoil protons that is obtained from the range measurements. When a neutron collides with a stationary proton the energy of the neutron is shared after the impact by both the particles. Only in a head on collision does the proton take up all the energy of the incident neutron. If En is the neutron energy and Ep that of a proton scattered at an angle γ to the original neutron direction, Ep is given by

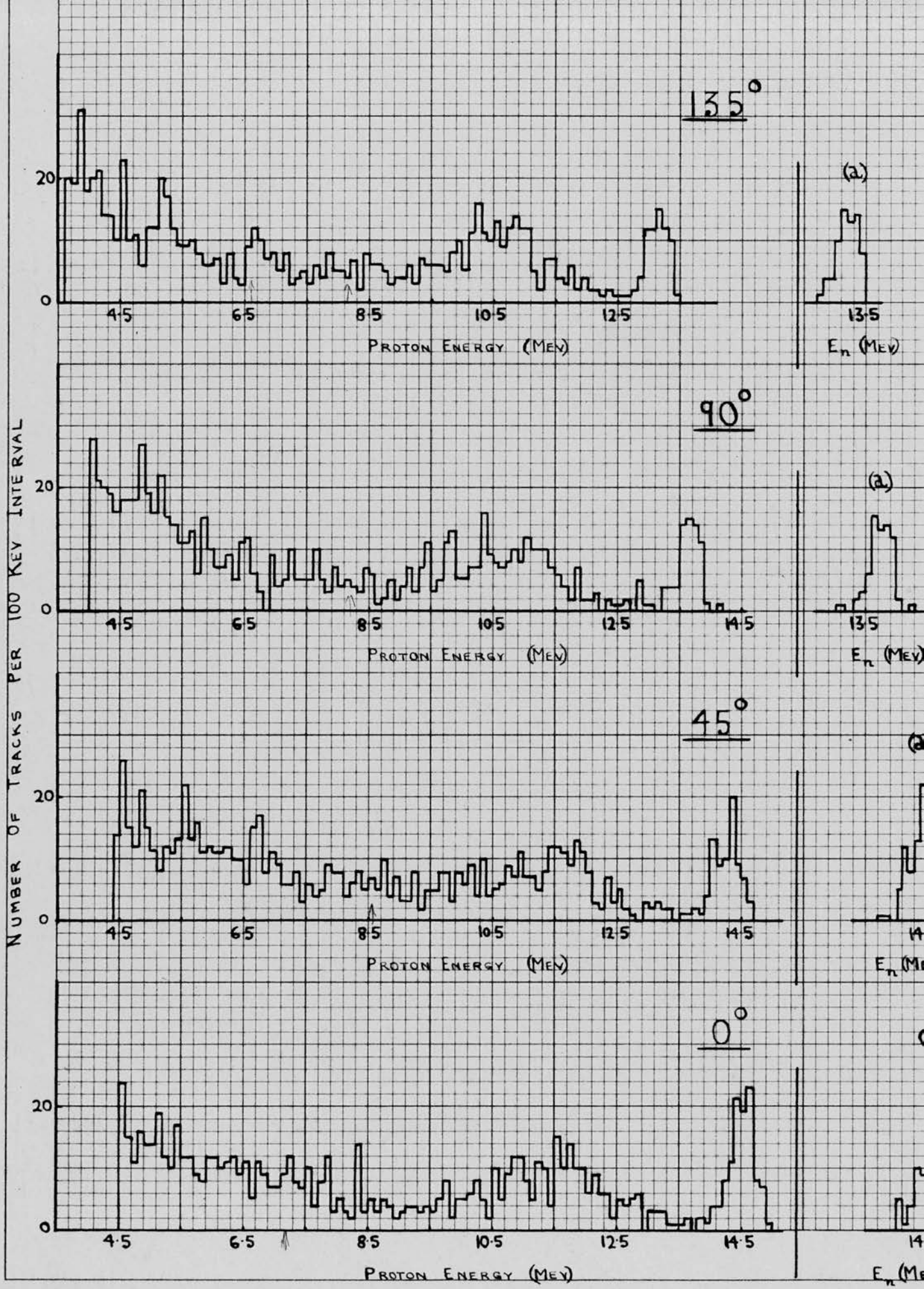


FIG. 3. RECOIL PROTON SPECTRUM

$$En = Ep \, Sec^2 \gamma \qquad (5.3)$$

For an angle of scattering of 5^0 it was found by numerical integration that the proton takes up 99.5% of the energy of the incident neutron. The correction that must be applied to the observed proton energies in order to obtain the energies of the neutrons incident on the plates, is therefore significant for Ep > 10 Mev.

Such a correction was applied to the protons belonging to the highest energy group in fig. 3 . Every track was taken up individually. From the known position of the track the direction of the neutron responsible for it, was determined. The neutron directions subtended angles of 0.5^0 to 1.5^0 with the length of the plate (this line being taken, as mentioned in sec. IV.1., as the line of reference in the eyepiece graticule against which all measurements of angles in the emulsion plane were made), the angle being larger in the case of tracks originating in those parts of the plate nearer the target or lying farther away from the target level. The recorded angle β was corrected accordingly to give the true angle β' between the neutron direction and the projection of the track on the plane of the emulsion.

The angle of scattering γ is related to the angles α and β' according to

$$Sec \, \gamma = Sec \, \alpha \, . \, Sec \beta' \qquad (5.4)$$

For convenience in obtaining the correction factor

$Sec^2\gamma$ of (5.3), values of log ($Sec^2\gamma$) were tabulated against values of α and β' from 0° to 7° at 0.5° intervals. With the help of this table the neutron energy E_n corresponding to each of the recoil proton tracks of the highest energy group, was deduced. These were plotted as before to indicate the number of neutrons against their energies as shown in fig. 3a.

VI. THE NEUTRON GROUP CORRESPONDING TO THE FORMATION OF Be^8 IN THE GROUND STATE

The observed distribution of neutrons belonging to the highest energy group in fig.3a show the following standard deviation of calculated energy (S.D.) at the different angles of observation θ with respect to the deuteron beam:

θ	S.D. (in Kev)	Target Thickness	Angle
0°	$\pm$ 195	±60	±6
45°	$\pm$ 185	±49.5	
90°	$\pm$ 175	±25	
135°	$\pm$ 180	±1.5	

These may be accounted for partly in terms of contributions due to the following factors:

1. The range straggling
2. The angular straggling
3. The thickness of the Li^7 target

VI.1. The range straggling.

Although charged particles may be ejected in any nuclear reaction with velocities which are constant within narrow limits, the ranges of the individual particles may not be the same. Every particle loses its energy in a large but finite number of steps during its passage through millions of atoms. Therefore the distance traversed for a given loss of energy will show

statistical fluctuations. This is referred to, as "range straggling" of the particles. These fluctuations become of greater importance in the emulsion, as compared to that in air, due to the finite size and relatively small number of the grains making up the track. The inhomogeneous distribution of the halide grains in the gelatin of the emulsion adds to the uncertainty in the exact value of the range. The possible random movements of the developed grains during processing, particularly when shrinkage of the emulsion takes place, contribute to the straggling.

In the calculation of the expected range straggling the treatment given by Bohr (1948) was followed.

According to Bohr the stopping effects on an atomic particle penetrating through matter can be said to be due to "nuclear collisions", in which momentum and kinetic energy are transferred to the stopping atom as a whole, and "electronic collisions" in which energy is transferred to the individual electrons of the atoms, resulting in atomic excitation and ionisation. It can be shown that the latter interaction plays the main part in stopping phenomena.

To consider the "electronic collisions", the various electrons in each atom are specified by an index s and I_s, the energy necessary to remove the s^{th} electron with charge ϵ and mass m from the atom by interaction with a particle of charge number Z, and velocity V, is used to

define what is called the "orbital velocity" u_s of the electron affected. u_s is given by

$$I_s = \tfrac{1}{2}\mu u_s^2$$

An expression is obtained for the stopping effect of the s^{th} electron and this in then extended to the Z_2 electrons in the atom to obtain the total energy loss $\overline{\Delta_\epsilon E}$, where the suffix ϵ stands for electronic collisions as distinct from nuclear ones.

The mean square deviation of the energy loss is given by

$$\Omega_\epsilon^2 = N \Delta R \; B_\epsilon \; T_m \; Z_2 \qquad (6.1)$$

where, N = the number of electrons per cm^3

ΔR = thickness of matter traversed,

and $B_\epsilon = \frac{2\pi z_1^2 \epsilon^4}{\mu v^2}$

T_m is the maximum energy transfer from the incident particle during an individual collision and is equal to $2\mu v^2$ for particles other than electrons.

The energy losses ΔE may be distributed according to a normal law of error,

$$W_o(\Delta E) = \frac{1}{\sqrt{2\pi}\,\Omega_o} \cdot e^{-\frac{(\Delta E - \Delta E_o)^2}{2\Omega_o^2}} \qquad (6.2)$$

with maximum ΔE_o and half width Ω_o. It will be so only if the individual contributions are small compared to Ω, i.e. if

$$\Omega > T_m$$

If this condition is not fulfilled the distribution will deviate from a Gaussian law.

Following an approximate treatment by defining a value T^* of T as

$$T^* = N \cdot \Delta R \cdot B_\epsilon \cdot Z_2,$$

Bohr gives the most probable values of the energy loss $\overline{\Delta^*_\epsilon E}$ and the width Ω^*_ϵ of the Gaussian peak as

$$\overline{\Delta^*_\epsilon E} = N \Delta R \, B_\epsilon \sum_s \text{Log} \left\{ \frac{1}{4} \eta_s^4 \frac{T^*}{T_m} \right\} \qquad (6.3)$$

$$\left(\Omega^*_\epsilon\right)^2 = N \Delta R \, B_\epsilon Z_2 \, T^*$$

where $\eta_s = \frac{2v}{u_s}$

It is concluded that the energy losses will actually have the distribution (6.2) if the incident particles are heavy ($m_1 \gg \mu$) and not too small fractions of the range are being considered.

Corresponding to a fixed amount of energy loss ΔE due to fluctuations in $\Delta_\epsilon E$ there will be a Gaussian distribution of the resulting values of ΔR, the mean square deviation of which is given by

$$\Omega^2_\epsilon(\Delta R) = \Omega^2(\Delta_\epsilon E) \left(\frac{\Delta R}{\Delta E}\right)^2$$

$$= P_\epsilon \Delta E \left(\frac{\Delta E}{\Delta R}\right)^{-3}$$

putting,

$$\Omega^2(\Delta_\epsilon E) = P_\epsilon \Delta R$$

since $\Delta_\epsilon E$ has the distribution (6.2).

14 Mev, L was found to be $\sim$ 16 in hydrogen; (6.5) gave the relative range straggling $\frac{\Omega}{R}$ of about 1.2%.

For heavier substances (6.6) gave in the case of protons $\frac{\Omega}{R}$ = 2%, independent of the initial velocity of the particles.

Considering the emulsion as a mixture of light and heavy materials, the relative range straggling for protons of energies 13-15 Mev can be taken $\sim$ 1.5%.

VI.2. The angular straggling.

The energy of particles emitted in a nuclear reaction depends on the direction of emission. Their observed ranges will vary accordingly. If the aperture of the camera or recording device is large, it will allow particles that enter in directions at a finite angle to one another. A wide band of particle ranges will therefore result. Such fluctuations can be considered as straggling of the ranges of the emitted particles and are termed as "angular straggling". This type of straggling has to be added to the straggling due to stopping phenomena (see sec. VI.1.).

In photographic plates it is possible to obtain very accurate geometrical conditions since the recording volume has small dimensions. In the present experiment the cross-section of the plates irradiated by the neutrons and subsequently examined was approximately 0.20 m.m. by 0.35 m.m. at a distance of 17.3 cm. from the neutron

source. The ~~position~~ portion of the target exposed to the deuteron beam was a circular area of diameter 1 cm. The angular uncertainty in the angular definition was therefore less than 1^{o}. Consequently the angular straggling can be taken as negligible.

This is a distinct advantage over other methods of neutron investigation.

VI.3. The thickness of the Li^{7} target.

Targets are called "thick" if the target thickness is considerable compared to the range of the incident particles in the target material. The particles emitted in the reaction have to make their way through a certain thickness of the target and therefore lose part of their energy. Consequently their observed ranges will be smaller. Only those particles produced near the surface of the target will have the full range.

The particles produced far inside the target have smaller observed ranges due to two reasons. Firstly, as mentioned above, they lose part of the energy before emerging from the target. Secondly, the energy of the incident particles is also decreased in penetrating to that depth and hence the energy imparted to the outgoing particles is reduced. According to Bethe (1937) a charged particle's efficiency in producing a nuclear reaction decreases nearly exponentially with the depth inside the target.

Due to these factors the particles, although produced by the same mode of a nuclear reaction will exhibit an energy spread. In such cases a so called "thick target" correction becomes necessary in order to obtain the actual distribution. A method of graphical extrapolation has been given by Bethe (1937) to correct for the target thickness and obtain corresponding thin-target energies.

In the present work no such major correction was needed. The Li^7 target used had a 0.22 m.gm./cm^2 loading. From the table of proton ranges in lithium given by Aron et al. (1949) the energy loss $\frac{dE}{dR}$ corresponding to 635 Kev deuteron energy was calculated by interpolation using the Gregory-Newton formula (Whittaker and Robinson; 1944, p.10). For the energy of the deuteron beam used in this experiment (E= 635 Kev), this gave a target thickness of 86 Kev.

The effect of this thin target on the deuteron energy was then estimated. Making use of the yield curve for the neutrons from the Li^7 (d,n) Be^8 reaction given by Trumpy et al. (1953), the average yield in arbitrary units was found out for a bombarding energy varying within limits of 592 ± 43 Kev. The intercept on the yield curve against this average yield, gave the average deuteron energy as 594 Kev. This value was used in all the calculations.

The target thickness of 86 Kev could cause a fluctuation in proton ranges of ~ 5μ at energies of ~ 14 Mev, for which energy the range was ~ 1000 μ.

Therefore the contribution to the straggling on account of this factor came to $\sim 0.5\%$.

VI.4. Straggling due to other factors.

The observed standard deviation of the range for the highest energy group amounts to about 2.2%, 2.1%, 2.2% and 2.4%. respectively, at the angles 0°, 45°, 90° and 135°. The calculated range straggling due to stopping effects in the emulsion accounts for $\sim 1.5\%$ in each case. The contribution of the target thickness to the straggling amounts to $\sim 0.5\%$.

Another factor contributing towards the observed straggling is the uncertainty regarding the point of origin of the track in the emulsion. It is possible that the first few grains, two or three, in exceptional cases even more, may not be rendered developable and will not therefore figure in the range measurements. Observations on the size of the grains gave the mean grain-centre to next grain-centre distance of $\sim 1.5\mu$. Consequently if the first two grains of a track of length $\sim 1000\mu$ may have been missed it amounts to a straggling of $\sim 0.3\%$.

These three factors put together thus account for $\sim 1.6\%$ out of the 2.1 - 2.4% observed straggling. The rest may be ascribed to the following:

(a) the inaccuracy in the determination of the depth angle θ (see sec. IV.1) at the point of origin of the

track inside the emulsion. Although maximum care was taken in measuring the depth difference across the first straight segment of the track and the error minimised by measuring across the maximum possible length of the segment, yet the smallness in magnitude of the depth difference ($\sim$ 1 depth scale division across a track length of 15μ) under the criteria set for the acceptance of tracks, will result in some error entering the observations.

(b) Contribution to straggling by the possible random movements of the grains of the emulsion during processing, particularly during fixation.

(c). Statistical fluctuations in the relative amounts of gelatin and the silver halide traversed by each proton.

(d). Any small angle scattering of the neutrons before they produced proton recoils.

VI.5. The energy resolving-power.

The standard deviations of the ranges were used to give the width at half height, of the corresponding energy distributions. These values corrected for the effects of target thickness are tabulated below along with the corresponding neutron energies.

θ	En (in Mev)	Peak width(in Kev)
0^{o}	14.60	445
45^{o}	14.35	420
90^{o}	13.70	400
135^{o}	13.15	410

The widths at half maximum (henceforward called width of the group) can by analogy with the corresponding optical problems be taken as a measure of the capacity of the method to distinguish between homogeneous groups of similar particles of different energy and can, in conformity with previous workers, be defined as the "energy resolving power" or simply as "the resolution".

To compare the resolution achieved in the present work with that obtained in other studies of $Li^7(d,n)\,Be^8$, the peak widths are shown in fig. 4 along with the average neutron straggling curve given by Bird and Spear (1955). This curve has been derived from the values of the width of neutron peaks from spectra published by a number of authors, the values having been corrected for the effect of target thickness.

The use of thick targets by Richards (1941) and Green and Gibson (1949) was responsible for ground state peak widths of 600 - 800 Kev (not shown in fig 4). Trumpy et al. (1953), Ihsan (1955, Bird and Spear (1955) and Gibson and Prowse (1955) observed ground state peaks of widths 470, 500, 430 and 300 Kev, respectively.

The resolution achieved in the present experiment is better than that in others, except that of Gibson and Prowse. Using experimental techniques exactly similar to those employed by others, these authors report a ground state group with a width of 300 Kev which falls much below the average neutron straggling curve in fig 4. The

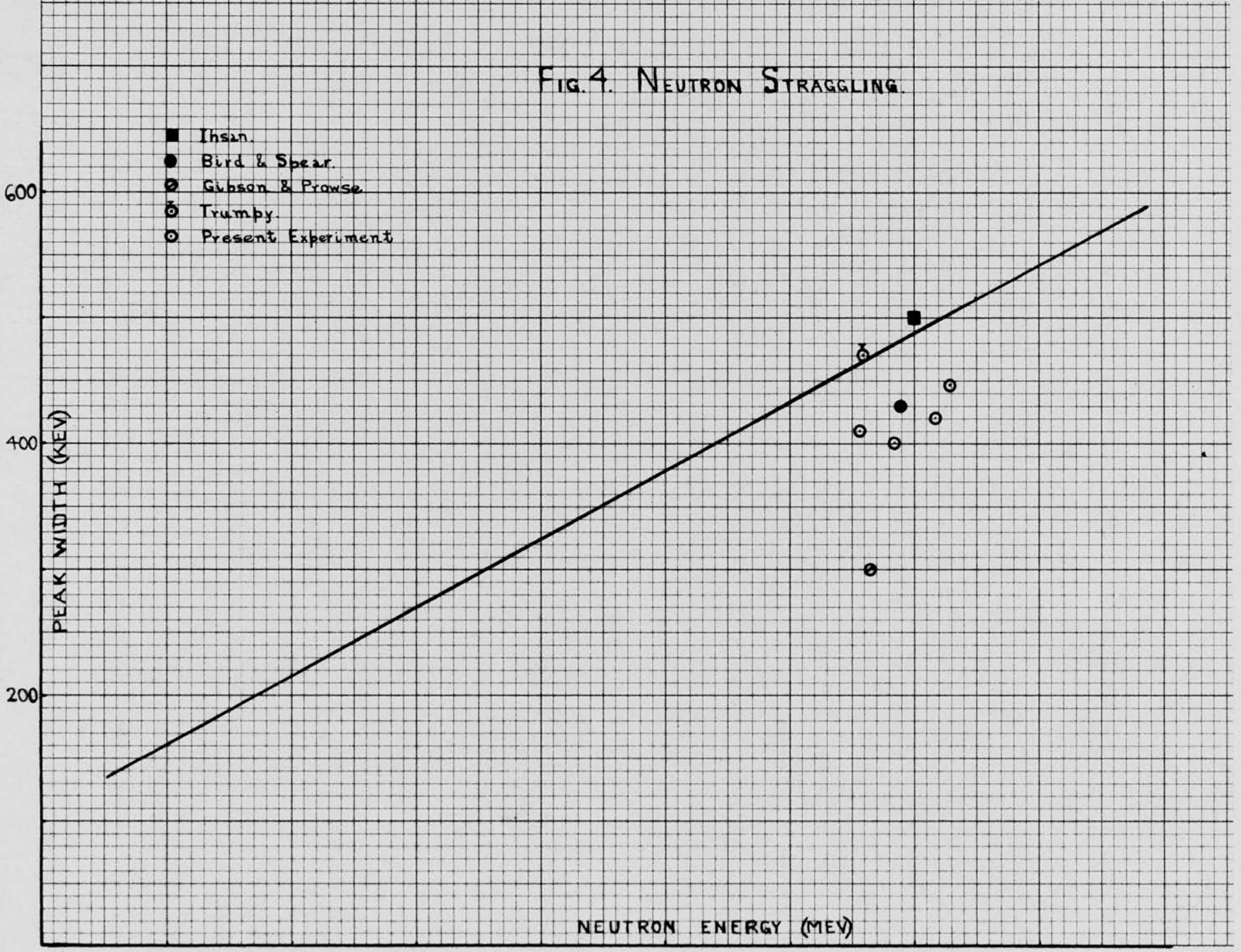


FIG. 4. NEUTRON STRAGGLING.
Ihsan.
Bird & Spear.
Gibson & Prowse.
Trumpy.
Present Experiment
600
400
200
PEAK WIDTH (KEV)
NEUTRON ENERGY (MEV)

values from the present experiment fall closer to this curve. The reason for such a fine resolution as achieved by Gibson and Prowse remains obscure.

VI.6. The accuracy of the range-energy relation.

The position of the highest energy neutron group in fig. 3. corresponding to the formation of Be^8 in the ground state can indicate the extent to which the range energy relation used, is correct. The mean neutron energy for the group is shown as E_n(Ob.) in column 2 in table 5 along with the angle of inclination θ between the photographic plate and the deuteron beam, θ being measured in the laboratory coordinates. The probable error in the observations is indicated.

Table 5

1	2	3	4
θ	E_n(Ob) in Mev	E_n(Cal.)in Mev	En(Cal)- E_n(Ob.) in Mev.
0^o	14.6 ± 0.13	14.66	+ 0.06
45^o	14.35 ± 0.14	14.38	+ 0.03
90^o	13.70 ± 0.14	13.73	+ 0.03
135^o	13.15 ± 0.14	13.11	- 0.04

The weighted mean of the Q values obtained from experimental data for the Li^7(d,n) Be^8 reaction is reported as $Q_o = 15.0 \pm 0.1$ Mev by Van Patter and Whaling (1954). This is in agreement with the Q value obtained from the mass defect of this reaction, using latest mass values

given by Li et al (1951:

Q_m = 15.017 Mev (Ajzenberg and Lauritsen: 1955).

Taking the Q value as 15.017 Mev, the neutron energies at the four angles of observation 0°, 45°, 90° and 135°, respectively, with respect to the deuteron beam, were calculated with the help of the relation (see appendix II)

$$E_n^{\frac{1}{2}} = 0.158\ E_d^{\frac{1}{2}} \cos\theta + (0.888\ Q + 0.665\ E_d + 0.025\ E_d \cos^2\theta)^{\frac{1}{2}}$$

The values of E_n obtained for the different angles are tabulated in column 3 as E_n(Cal.) and shown in fig. 5 against the corresponding angle θ.

It is noticed that the difference between the observed and calculated values of E_n lies well within the range of experimental error in each case. This complete agreement between the two values, points to the correctness of the range-energy relation used.

In the procedure followed for deducing the neutron energies of the recoil protons, the moisture content of emulsion has not been so far taken into account. From the observations of the mass and volume of the model plate, the density of the emulsion was determined (see sec. V.1.). As all the plates were taken from the same batch, the density of the emulsion in the plates irradiated, could be taken to be reasonably the same. This density of the emulsion came out to be 3.69 gms. per c.c.. The range-energy relation for C2 emulsions given by Wilkins from which, that for G5 emulsions used in the present work, was deduced, is for an emulsion density of 3.92 gms. per c.c..

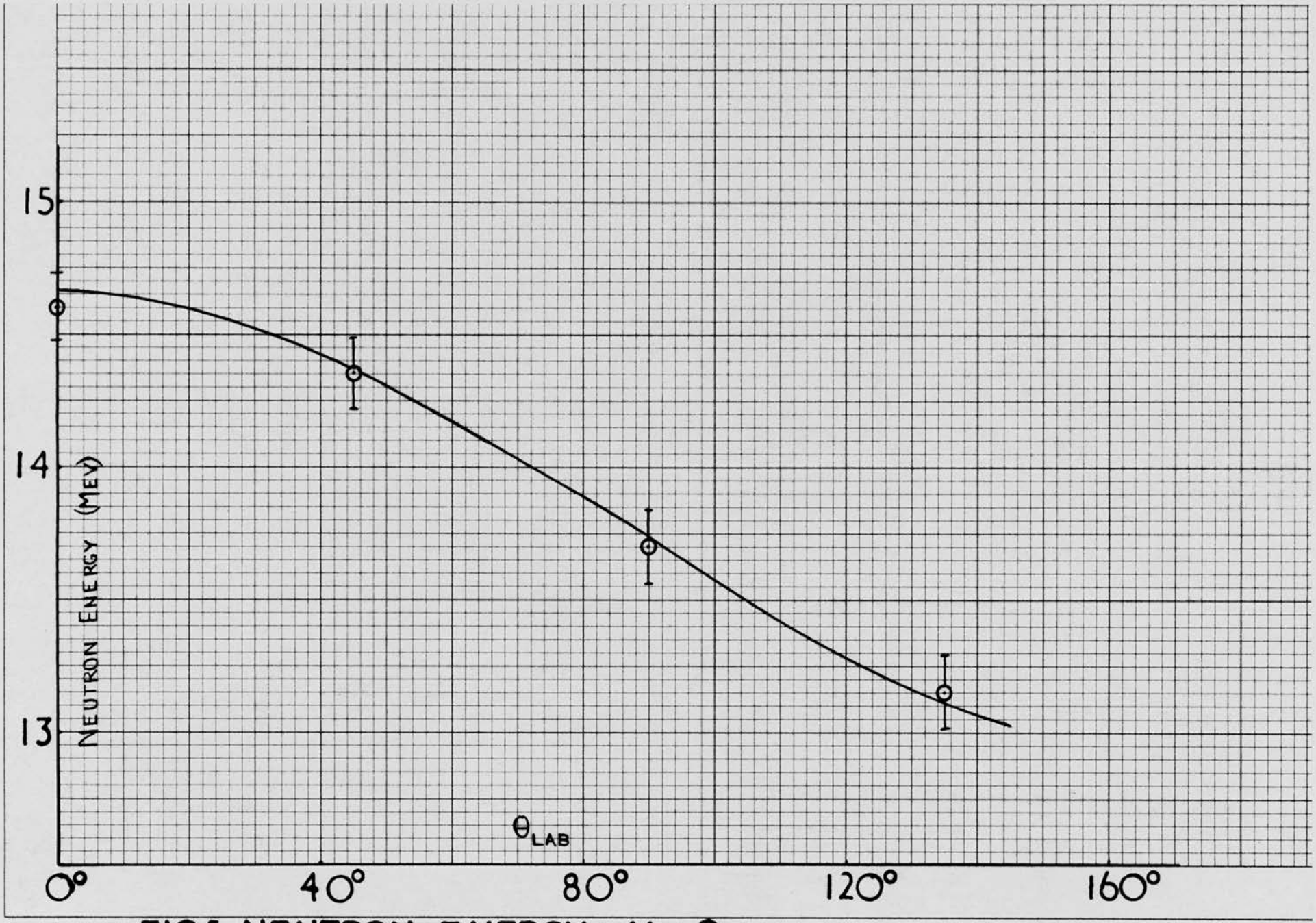


FIG.5. NEUTRON ENERGY V. θ_{LAB}

If the correction for this change in emulsion density were applied, as was originally intended, it is found that the integral stopping power of the emulsion, S, decreases with decrease in emulsion density ρ in the following ratio (Wilkins, 1951: table 10):

$$\frac{S_{\rho=3.92}}{S_{\rho=3.77}} = \frac{1}{0.975} \quad (= \frac{1}{f}, \text{ say})$$

in the proton energy range 5 to 15 Mev. For a still lower density of emulsion, viz. 3.69 gms. per c.c., the factor $f = \sim 0.96$.

From the definition of the integral stopping power of an emulsion, the range R of a particle in the emulsion is given by

$$R = \frac{Ra}{S}$$

where R_a is the range in standard air for the same particle energy.

As the range in the emulsion is inversely proportional to the integral stopping power, for a certain initial energy any particle will have a longer range in an emulsion of lower density, or, in other words, a given length of track will correspond to a lower initial energy of the particle for a lower density emulsion. If such a correction is applied to the present measurements, the neutron energies corresponding to the observed recoil proton tracks will be lower than that shown in table 5

It is noticed that there is a better agreement between

the observed and calculated values of E_n when the difference in emulsion density is not taken into account. It seems that the change of emulsion density from 3.92 to 3.69 gms. per c.c. compensates for the inaccuracy of the range-energy relation of Wilkins, so that his tabulated ranges are slightly higher ($\sim 4\%$) for the indicated density, 3.92 gms. per c.c., of the emulsion.

VII VARIATION OF NEUTRON-PROTON CROSS-SECTION WITH ENERGY

The neutrons are detected in the nuclear emulsions by noticing the ionisation caused by their recoil protons. Their numbers and energies are derived from the corresponding proton tracks. If a large number of neutrons with different energies are incident on the H atoms how many of them, and which, will give rise to recoil protons will depend on the probability of impact, or in other words, on the neutron-proton (np) cross-section.

The n-p cross-section varies with change in neutron energy, decreasing with increase in energy. Hence there is a greater probability of a lower energy recoil proton being recorded as compared to one with high energy. The observed histograms must therefore be corrected for the variation of n-p cross-section with energy in order to obtain the actual distribution.

The chief contribution towards the total cross-section σ_t for neutron-proton interactions is of the n-p scattering cross-section. The cross-section for the competing process like radiative capture reaction. $H^1(n,\gamma)H^2$ is very small and decreases with $^1/_V$ for slow neutrons, V being the neutron velocity. For fast neutrons ($E > \frac{1}{2}$ Mev) it is negligible (Bethe, 1937).

For the neutron energy range met with in the present work, the total scattering cross-section has been experimentally determined by Aoki (1939), Salant and

Ramsay (1940), Bailey et al. (1946), Ageno et al. (1947) and Sleater (1947). These values along with some others, have been compiled together by Adair (1950), most values in the neutron energy range 6.0 to 22.0 Mev being provided by Sleater.

Green and Gibson (1949), Trumpy et al. (1952) and Gibson and Prowse (1955) all of whom studied $Li^7 + D^2$ reaction used the n-p cross-section values given by Sleater (1947).

For the present work the values of n-p cross-section, shown as a function of the laboratory kinetic energy of the incident neutrons by Adair (1950), have been used. The total cross-section was found to vary from ~1.9 barns at 4.05 Mev to ~ 0.6 barns at 15.05 Mev neutron energy. The relative numbers of neutrons [redacted] at each individual energy was obtained by dividing the observed number by the appropriate cross-section at that energy. The corrected number-energy distribution of neutrons [redacted] was then smoothed.

VIII SMOOTHING OF OBSERVED DATA

The results of the measurements on the tracks at this stage, are presented as a frequency histogram. It exhibits groups of monoenergetic particles, some groups featured prominently, others not so clearly demarked. The question is how to decide from the amount of structure noticeable in some portion of the histogram, whether it represents a genuine feature of the distribution of events that are being studied or it is simply due to statistical fluctuations. For an enormous number of observations the details appearing in the histogram can be taken as true since the effect of statistical fluctuations would be absolutely inappreciable. For the cases in which the number of events is not large. no definite conclusions can be drawn about the merits of the "ups" and "downs" noticeable in the histogram.

Smoothing helps to reduce the contributions of the statistical fluctuations. Mainly the true distribution of events will be described by a smooth curve, the statistical fluctuations will usually appear as small bumps. Such a curve retains fully the principal features of the observed histogram.

This graduation or smoothing of experimental data is brought about by fitting (in the least squares sense) the best polynomial of degree j to each set of (2n+1) adjacent points ($2n+1 > j$) and then taking the value of

the polynomial at the centre of the set, as the smoothed value for that point. By varying j or the number of points (2n + 1), different degrees of smoothing can be applied. Depending on how much of the detail is desired to be suppressed, the degree of smoothing can be decided.

But this procedure is rather arbitrary. When the observed histograms (fig. 3) were smoothed according to the seven term relation (Whittaker [redacted] and Robinson, 1944)

$$U_o^1 = \frac{1}{21}[7U_o + 6(U_1 + U_{-1}) + 3(U_2+U_{-2})-2(U_3+U_{-3})] \quad (8.1)$$

the curve obtained showed a number of "peaks" and "valleys". Some of the peaks could have been taken, erroneously perhaps, as a genuine property of the distribution although they might have resulted from the statistical fluctuations.

The extent to which statistical fluctuations could influence an observed distribution, can be estimated by determining the effect of different degrees of smoothing on a random sample from a known population. If such a population could be constructed and if its distribution resembled that of the one being dealt with, one could decide whether of not smoothing was of any use, and if so, which smoothing method to prefer.

Random sequences of integers are available in published tables. A sample of 250 successive integers lying between 0 and 99, both included, was chosen from the random sequence given by Fisher and Yates (1949). The integers were arranged in 50 equal intervals, the first interval

accomodating the integers 0 and 1, the second integers 2 and 3, and so on. This yielded the histogram (fig. 6a) with an average density of population per interval, henceforward called "the density of events", of 5. The number 5 was chosen since that was the average density of events in the observed histograms (fig.3) in the neutron energy region ~6-10 Mev for which, as mentioned earlier in this section, interpretation was uncertain.

Applying the smoothing according to relation (8.1) to the data represented by fig (6a) yielded a curve (fig. 6b) which showed density variations of~± 3 in 5, i.e., amounting to ~60%. A second sample similarly constructed with 250 integers, different from the first lot, showed variations of ~54%. An interpretation based on the smoothed curve (6b) would report a preference for certain integers. Such a deduction is erroneous, as in the true distribution of the integers the occurrence of every integer is equally probable. It is therefore seen that if the smoothing relation (8.1) is used for any data with an average density of events of 5, statistical fluctuations amounting to even 60% can occur.

Application of Spencer's 21-term smoothing formula (Whittaker and Robinson, 1944) to the sample (6a) yielded the curve shown in fig. (6c). The fluctuations decrease to ±1.5, i.e., to ~ 30%. It is therefore concluded that in the case under consideration a stronger smoothing is better suited. Although the fluctuations still remained

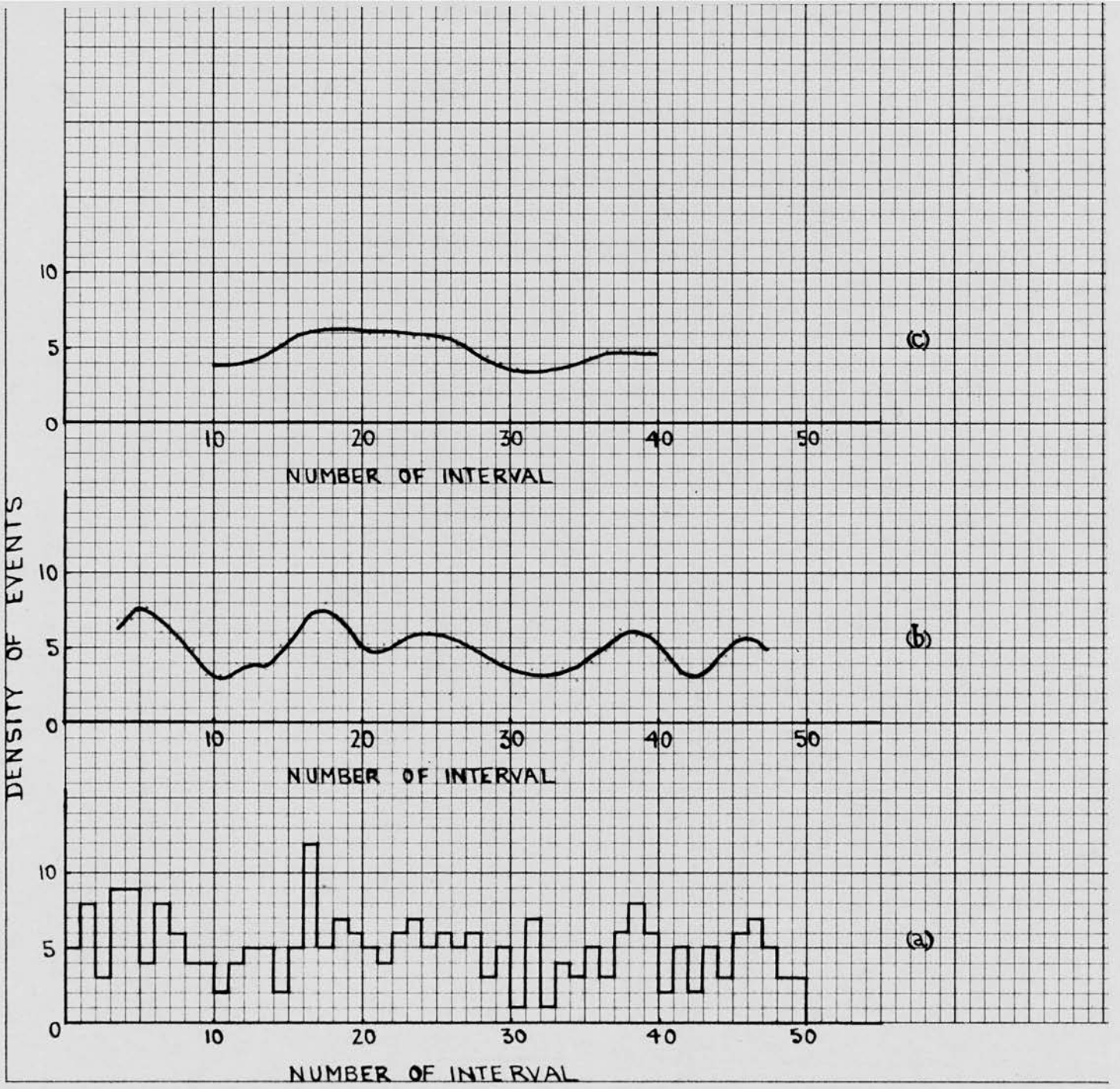


FIG. 6. SAMPLING HISTOGRAM AND SMOOTHED CURVES

the smoothed curve obtained is the nearest approach to the true distribution.

To find out the extent of the statistical fluctuations in a larger sample, a population of 2500 integers was constructed with an average density of 50. It was noticed on smoothing the data according to Spencer's 21-term formula, that the smoothed curve deviated from the true distribution by $\sim \pm 5$, so that the effect of statistical fluctuations was limited to about 10%.

The above results can be summarised as follows:

The "peaks" and "valleys" noticeable in smoothed curves may in many cases, not be a true representation of the actual distribution; they may just result from statistical fluctuations, whose effect can be minimised by making a larger number of observations, and in the case of a given sample, by applying a smoothing of a higher degree.

Taking a concrete example, if in a smoothed curve a peak were observed with a height of three units in excess of the troughs on either side, it could be deemed as genuine only when the average density of events was $\geqslant 12$, since the statistical fluctuations for this average density can come to $\sim \pm 2.5$, this value being deduced from the 30% and 10% possible fluctuations noticed above for average densities of 5 and 50, respectively.

The experimental data for $Li^7(d,n)Be^8$ can now be analysed in this light.

Trumpy et al. (1953) applied a smoothing by combining

each ordinate in the energy distribution with the two neighbouring ones by giving the ordinate and the mean value of the two others the same weight. This will effect a smoothing of a weaker degree. For the curves obtained by the authors with such a smoothing, in the neutron energy region near 10 Mev, the statistical fluctuations can amount to $\sim 30\%$ or even more for the corresponding average density of events. Trumpy et al. report levels in Be^8 at 2.3, 4.1, 4.9 and 7.6 Mev besides the ground state and the well known 2.9 Mev level. Taking into consideration the 20-25% correction that was applied for tracks lost from the surface of the emulsion and the $\sim 30\%$ possible contribution of the statistical fluctuations, the evidence for the levels other than the clearly demarked ground and 2.9 Mev states can not be taken as conclusive. The observed spectra can be interpreted in terms of a broad 2.9 Mev level.

In the experiment of Catala et al. (1953) the correction factor for tracks that escaped from the emulsion surface is nearly twice that in the case of Trumpy et al. It is therefore difficult to estimate the correct average density of events from the published histograms, the peaks noticed in the histogram having been reported by the authors in terms of levels in Be^8. There is a considerable possibility of some of the peaks, particularly those that are not clearly demarked but have been taken as an indication of a fine level structure in Be^8, having

resulted due to statistical fluctuations.

It would have been of great interest to find the extent of possible statistical fluctuations in the results published by Gibson and Prowse (1955) as these authors have achieved a resolution of 300 Kev which has not been obtained by other investigators using the same techniques. It is not possible to analyse their data in this manner as, what seem to be the relative number of tracks in each interval, and not the absolute intensities, are provided. The total number of tracks measured has not been mentioned either.

The histograms (fig.3) obtained in the present experiment were smoothed using the Spencer 21-term formula after the correction for variation of n-p cross-section with energy (see sec. VII) had been applied. The number-energy curves are shown in fig 7. The 2.9 Mev level is clearly indicated. There is only a slight indication of the 4.9 and 7.5 Mev levels found in other investigations. Because of the possibility of statistical fluctuations amounting up to $\sim 30\%$ for the average density of events in this case, little significance can be attached to these minor peaks. In fact within the limits of statistics a smooth curve can be drawn (thick curve in the fig) representing the events of fig.7 and showing only the ground state, the broad 3 Mev level and another broad level at about 10 Mev. The contribution of the direct three particle break up of the intermediate nucleus Be^9

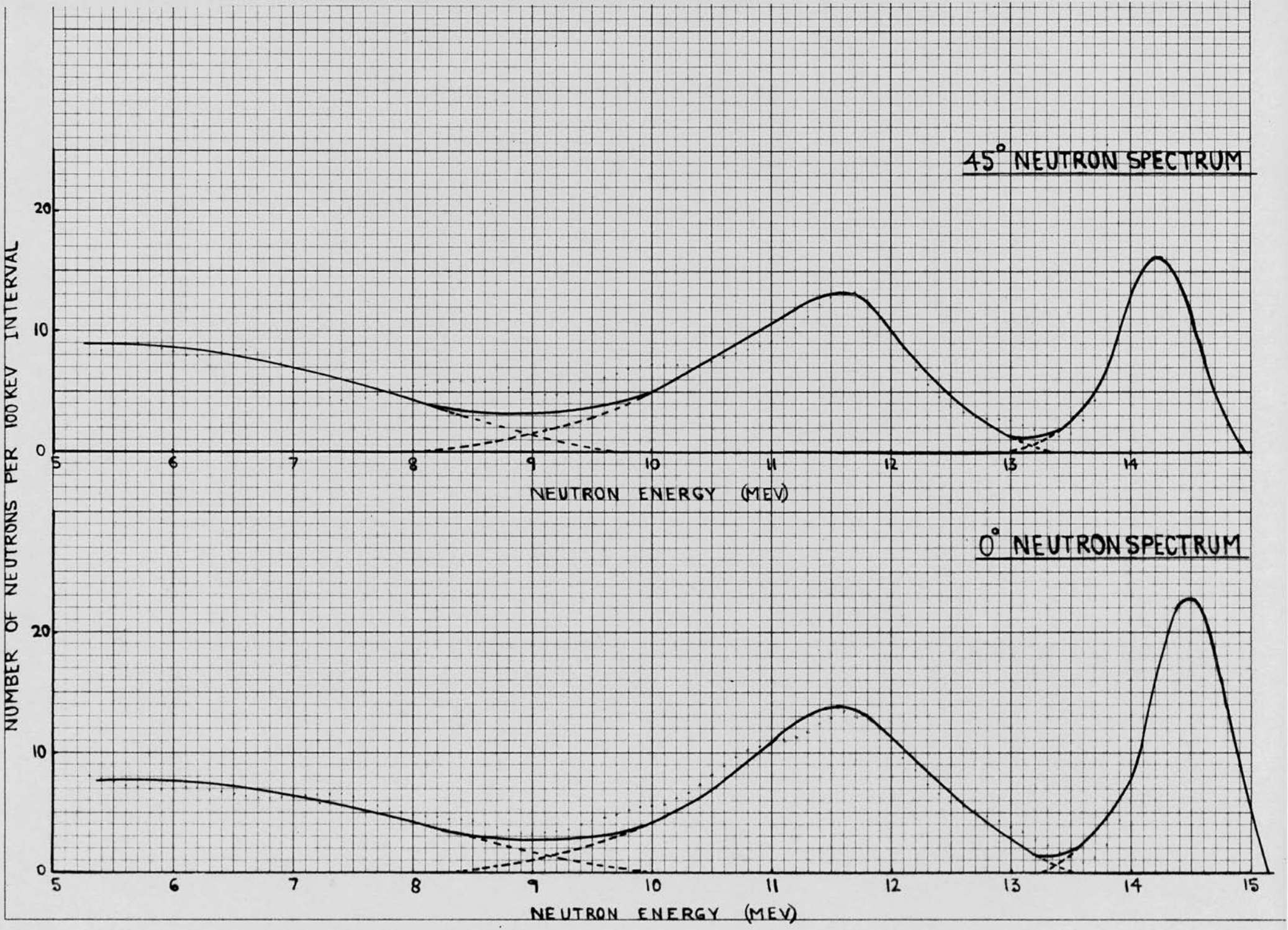


FIG. 7. ENERGY SPECTRUM OF NEUTRONS FROM $Li^7(d,n)Be^8$

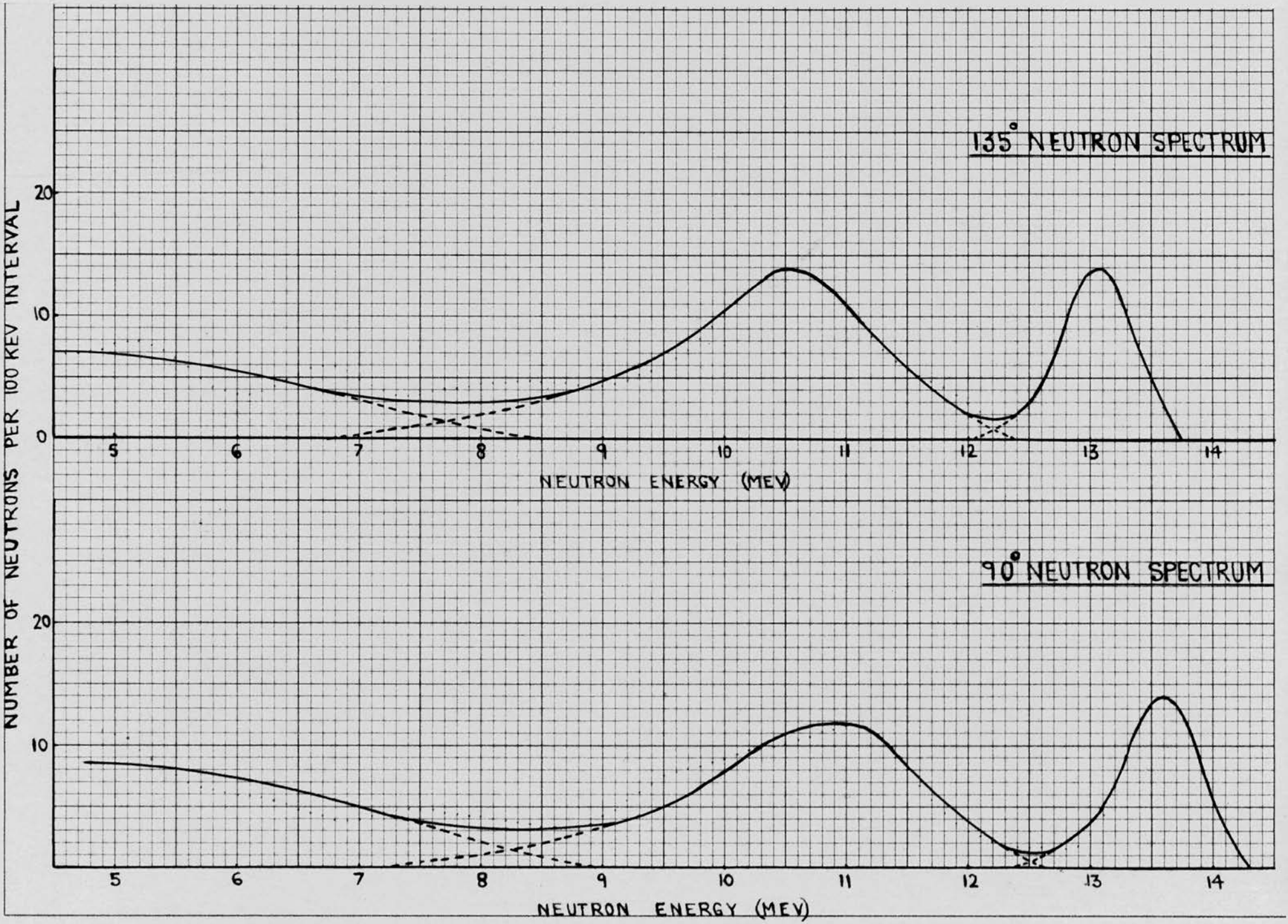


FIG. 7. ENERGY SPECTRUM OF NEUTRONS FROM $Li^7(d,n)Be^8$.

appears to be very small indeed.

[redacted]. Also it has been noticed for the $B^{10} + D^2$ reactions, which can proceed according to $B^{10}(d,\alpha)Be^8$ and $Be^{10}(d,\alpha)2He^4$, that less than 5% of the disintegrations observed are according to the single process three-particle break up (Ajzenberg and Lauritsen, 1955).

The particle groups corresponding to the three levels are shown (dotted curve) in fig. 7. The widths of the ground state are between 700 and 750 Kev at the different angles. Subtracting this experimental width from the width of the group at 2.9 Mev, a true width of 1.3 Mev is obtained for this level.

The mean life τ of a level is given by

$$\tau = \frac{\hbar}{\Gamma}$$

where Γ is the level width and $\hbar$ is Planck's constant divided by 2π (Evans, 1955). This gives the mean life of the first excited state of the order of 10^{-22} second.

Moak and Wisseman (1956) give a width of about 2 Mev for a broad state in Be^8 near 12 Mev. This is in good agreement with the approximate width of the broad 10 Mev level (fig.7) observed in the present experiment.

VIII.1. Discussion of results.

A summary of the results from various studies on the

neutrons from deuteron bombardment of Li^7 was given in sec. I.3. It is noticed that only Catala et al. (1953) have claimed a fine level scheme for Be^8 with levels at 1.5, 2.2, 2.9, 3.4, 4.1, 5.3 and 7.5 Mev. The levels other than those at 1.5 and 3.4 Mev have been reported by Trumpy et al. (1953) and Gibson and Prowse (1955).

As mentioned earlier in this section (p. 65), application of a weak smoothing to the data obtained in the present work (fig. 3) yielded curves from which inferences on the same line as that of other authors could have been drawn. But considering the extent of statistical fluctuations that could possibly come in, such a deduction from the present experiment can not be regarded at all as conclusive. Similar statistical fluctuations, but of varying degrees, are likely in other investigations as well.

The present work therefore indicates that there are only three states in Be^8 below 12 Mev excitation, this result being at variance with those from other studies of the same reaction. It is in agreement with results from many different experiments such as: $Li^6(He^3,p)Be^8$, $Li^7(p,\gamma)Be^8(\alpha)He^4$, $Li^8(\beta)Be^8(\alpha)He^4$, $Be^9(d,t)Be^8$, $B^{10}(d,\alpha)Be^8$, $B^{10}(\gamma,d)Be^8$, $B^{11}(p,\alpha)Be^8$ and $B^{11}(\gamma,t)Be^8$, (see Table 1, sec. I.4.). A few of these experimental results may be mentioned.

The reaction of $B^{10}(d,\alpha)Be^8$ has been studied by Cuer et al. (1954), Holland et al.(1955) and Bockelman and

Leveque (1956). The two latter experiments report only the ground and 2.9 Mev states. Holland et al. state that a peak with nearly 10 per cent, in some cases even two per cent, of the intensity of the ground state transition would have been detected. The far better statistics favour their results.

The work of Inall and Boyle (1953) is in disagreement with that of La Vier et al. (1956) who studying the same reaction $Li^7(p,\gamma)Be^{8*}(\alpha)He^4$ find no alpha groups other than that corresponding to the 2.9 and 10 Mev states. La Vier et al. point out that the minimum intensities of the alpha-groups, corresponding to levels in Be^8 at 4.1, 5.3 and 7.5 Mev, which they would have been able to observe, are 1%, 0.5% and 0.5%, respectively, of the total alpha-intensity. The observed intensities reported by Inall and Boyle are respectively 1.8%, 1.7% and 1.0%.

Other recent work of Moak and Wisseman (1956) on $Li^6(He^3,p)Be^8$, Malm and Inglis (1953) and Holland et al. on $B^{11}(p,\alpha)Be^8$, Gilbert (1954) and Frost and Hanna (1955) on $Li^8(\beta)Be^8(\alpha)He^4$ and Gelinas and Hanna (1956) on $Be^9(d,t)Be^8$ give evidence only for the 2.9 Mev level in Be^8 up to an excitation of 8 Mev.

Experiments of Moak and Wisseman and La Vier et al. already mentioned above, indicate also a broad level in Be^8 in the vicinity of 10-12 Mev. Moak and Wisseman would have observed other levels below 14 Mev excitation if their intensities were 1-3% of the transition to the

2.9 Mev state.

The accurate phase-shift analysis of the $\alpha - \alpha$ scattering cross-section data by Nilson et al.(1958) produces evidence only for three, namely the ground, 2.9 Mev and 10 Mev states below 12 Mev excitation. The existence of a 7.5 Mev state as proposed by Steigert and Sampson (1953) from a similar investigation is excluded.

It is thus seen that all recent work lends support only to the ground, 2.9 Mev and 10 Mev states in Be^8 up to an excitation of 12 Mev.

Isotopic spin considerations, in some cases, provide information on the energy level sequences of an isobaric set of nuclei, all with the same mass number A. The ground state of Li^8 with isotopic spin T = 1 matches in energy the 16.72 Mev (T=1) state in Be^8. This level lies beyond the energy range explorable in the present experiment. For the low lying states in Be^8, T=0, in accordance too with their breaking up into two alphas.

A discussion of allowed alpha-particle rotational states in Be^8 has been given by Wheeler (1937). The rotational energy is given by

$$E_R = \frac{\hbar^2}{2A} J(J+1) \qquad (8.2)$$

where A is the moment of inertia of the nucleus and J is the angular momentum. Only levels with even J are allowed because of symmetry requirements of the rotational and vibrational wave functions. Wheeler stated that only

the lowest vibrational state would be expected to have a long enough life to be observable and that rotational levels above J=4 may be too much widened by dissociation to be of interest.

The excitation energies of the first two rotational states given by (8.2) are in the ratio 3:10 for J= 2 and 4. The energies of the excited states in Be^8, according to the present work, are in the ratio 2.9:10. Thus the agreement with the values predicted on the basis of a rotational model is complete.

According to Kurath (1956) a central force model with intermediate spin-orbit coupling accounts for levels in Be^8 with J=0, 2 and 4, and excitation energies of about 0,3 and 10 Mev, respectively. There are no calculated levels corresponding to the observed states at 4.2,5.4 and 7.5 Mev.

This is also consistent with the present results.

IX GENERAL THEORY

Bohr in 1936 was the first to develop the concept of a compound nucleus, as an intermediate system of relatively long life, on the basis of which nuclear transmutations caused by charged particles could be explained. When a target nucleus A is bombarded by an incident particle a, the two combine to form a compound nucleus C, whose excitation energy depends on the bombarding energy. It is assumed that in the compound nucleus C there are strong interactions between all the nucleons, the incident particle losing its independent identity. This semi-stable compound system has a mean life ($\sim 10^{-16\pm3}$ sec) which is long compared to the time for a proton to cross the nucleus ($\sim 10^{-22}$ sec). The same compound nucleus C, in the same level of excitation, can also be formed by the impact of some other particle on a different nucleus. According to Bohr the properties of the compound nucleus are independent of its mode of formation.

The compound nucleus next dissociates into an outgoing particle and a residual nucleus. This dissociation can generally take place in a large number of competing ways, the latter being decided according to the conservation laws for charge, mass number, energy, and momentum.

There is another property of the compound nucleus model: resonance. If the energy of incident particle is such that

the total energy of the system is just equal, or nearly equal to that of, one of the energy levels of the compound nucleus the probability of the formation of the compound nucleus will be much greater than if the energy of the particle lies in the region between resonance levels. This will result in fluctuations of the yield of every nuclear process with the energy, highest yield being at the resonance energies.

From the study of resonance phenomena, the spacing between neighbouring levels of the compound nucleus can be obtained. The distribution in excitation energy and the modes of formation and decay of the energy levels will be helpful in understanding how nuclei are constructed and how the various particles within the nuclei interact.

The width of resonance levels is of considerable interest. The width of a level gives the total probability of the emission of particles of any kind - protons, neutrons, alpha-particles, γ-rays, etc. by the compound nucleus. The relative probability of the emission of the different types of particles can also be obtained.

A nuclear disintegration can be represented schematically, as

$$A + a \longrightarrow C \longrightarrow B + b \qquad (9.1)$$

The compound nucleus C formed by the impact of the incident particle a, on the initial nucleus A, splits

into an outgoing particle b and a residual nucleus B.

The processes initiated by the particle a may be classified into two types. If the outgoing particle b is a light quantum, the process ~~if~~ is known as the "simple capture" of particle a. In the case of emission of a material particle, it is "particle disintegration". When the outgoing particle is identical with the incident one it is a scattering (elastic or inelastic) process, this being a special case of particle disintegration.

A consequence of the conservation of energy and momentum is that in the simple capture process nearly all the energy is carried away by the light quantum b and practically all the momentum by the nucleus B. Energy and momentum are shared by both the nuclei B and b in the case of particle disintegrations.

In any nuclear process, the residual nucleus B can be left either in the ground state or in an excited state. The latter can be any out of the many excited states energetically possible and allowed by selection rules. There will be a group of outgoing particles b, with a certain definite energy, corresponding to each excited level of nucleus B. The group with highest kinetic energy will correspond to the nucleus B being left in the ground state, and the other groups, of decreasing kinetic energy correspond to excited states of nucleus B of increasing excitation energy. This will hold for both "simple capture" and "particle disintegration" processes.

By measuring the kinetic energies of the various groups of the outgoing particles, or the spectrum of the γ-rays from the simple capture process, the excited energy levels of the final nucleus can be determined.

If the residual nucleus B is left in an excited state, it may behave in either of the two ways depending on its level of excitation. If the excited state is below the dissociation limit, light quanta are the only particles that can be emitted. The residual nucleus will emit one or more γ-rays until it finally arrives in its ground state. The observation of the spectrum of γ-rays provides an important check on the scheme of energy levels of nucleus B deduced from the groups of particles emitted in the main nuclear process.

If the residual nucleus B in the main nuclear process is left above its energy of dissociation, it may break up further, according to the scheme

$$B^* \longrightarrow D + d \qquad (9.2)$$

emitting material particles. That the nucleus B is in an excited state is denoted by the asterisk, D is the second residual nucleus and d is the second emitted particle.

The main and secondary processes can also be regarded as taking place in one step according to the scheme

$$A + a \longrightarrow [\,B^*\,] \longrightarrow D + d + b \qquad (9.3)$$

An example of a direct three particle disintegration is

$$X(Z,A)+d \longrightarrow C(Z+1,A+2) \longrightarrow \begin{cases} Y(Z+1,A+1)+n \\ Y(Z,A+1)+p \\ Y(Z-1,A-2)+\alpha \end{cases} \qquad (9.6)$$

Because of the special peculiarities, processes other than (9.6) can take place in this case. The loosely joined deuteron structure dissociates in the external field of the target nucleus and only one of its constituents is captured. On account of the finite size of the deuteron it may happen that one constituent comes into contact with the nuclear surface before the other one does and be quickly absorbed because of the high nuclear interaction energies. The second nucleon may or may not hit the nuclear surface. If it does hit, the compound nucleus C(Z+1,A+2) will result according to (9.6). If the second nucleon misses, either nucleus C' or C" will result according to the process

$$X(Z,A)+d \longrightarrow C'(Z,A+1)+p \qquad (9.7a)$$

$$X(Z,A)+d \longrightarrow C''(Z+1,A+1)+n \qquad (9.7b)$$

The resulting compound nuclei C' and C" may break up further, emitting some other nuclear particle. Out of the processes (9.7a), (9.7b) the previous one is more probable, particularly at low energies, as the electrostatic repulsion acts only on the proton.

In general the term "stripping" is used for such reactions. The cross-section for these processes is especially simple to compute at very high deuteron energies when the Coulomb repulsion between the nucleus

and the deuteron can be neglected. Then the deuterons move in straight lines with constant speed until they collide with the nucleus. At lower deuteron energies the effect of the Coulomb field is considerable. The main difficulty lies in finding the mathematical form of the wave function of the deuteron near the nucleus. Several attempts involving approximations have been made notably by Peaslee (1948) and Butler (1950,1951). There is no satisfactory theory yet on the basis of which cross-sections of these processes can be calculated.

a). Energetics of stripping reactions.

In the (d,p) stripping reaction in which a neutron with orbital angular momentum l_n is accepted by the target nucleus, the direction in which the proton proceeds is determined by l_n and its energy by the reaction energy Q for the formation of the level into which its companion was captured. Analogously in the (d,n) stripping reactions, the directions of the escaping neutrons will be determined by the orbital angular momentum l_p contributed by the captured proton. The energetics of processes (9.7a,9.7b) are therefore indistinguishable from those in which a compound nucleus is formed and subsequently disintegrates.

b). Angular distribution in stripping reactions.

The angular distributions of the product particles are entirely different in stripping reactions and in compound nucleus reactions. The angular momentum l_n or l_p

transferred by the captured particle in stripping reactions, decides the direction of the emitted particle. The angular distribution does not have a fore-and-aft symmetry about $\theta = 90^{\circ}$ but shows a pronounced forward maximum.

The applicability of the Oppenheimer-Phillips (O-P) theory is restricted to heavy nuclei. For light nuclei ($Z < 30$), according to Bethe (1937) the difference between the O-P theory and the ordinary theory is unobservably small. Cases are known in light elements, where the deuteron produces a compound nucleus. As the Coulomb barrier is not high enough to prevent direct formation of a compound nucleus, resonances may occur as they do in the case of other particles. For certain deuteron energies particularly those away from the resonances, it is possible that the reaction proceeds partly through the compound nucleus mechanism and partly through stripping.

IX.2. The selection rules.

The selection rules that hold generally for any "coupling scheme" in the nucleus, relate to the total angular momentum and the parity of the initial nucleus, incident particle, final nucleus and outgoing particle.

Considering as before (p.76) a reaction to be represented schematically as

$$A + a \longrightarrow C \longrightarrow B + b,$$

let the quantum numbers I_1, i_1, i_2, I_2 denote respectively the intrinsic nuclear angular momentum of each of the four

particles A,a,b, and B. On the entrance side let l_1 represent the mutual orbital angular momentum between A and a, and similarly l_2 on the exit end between the products B and b. The vector sum of I_1 and i_1 can have any value between $|I_1-i_1|$ and $|I_1+i_1|$ and the particular value that it does have is called the entrance "channel spin" s_1. Similarly there is a value s_2 for the exit channel spin. According to the conservation law,

$$s_1 + l_1 = I_o = s_2 + l_2 \qquad (9.8)$$

where the quantum number I_o denotes the angular momentum of the intermediate level.

This law (9.8) leaves too many possibilities. The possible values of l_1 and l_2 are restricted to a certain extent by the parity rule. For the reaction

$$Li^7 + D^2 \longrightarrow Be^{9*} \longrightarrow Be^8 + n^1$$

the ground state of Li^7 has spin $\frac{3}{2}$ and odd intrinsic parity, the deuteron has unit spin and even parity, the ground state of Be^8 is 0^+ (the superscript + denoting even parity) and neutron has a spin of $\frac{1}{2}$ and even intrinsic parity. So that the nucleus changes parity from odd to even. The notation "yes" denotes that the parity changes (from even to odd or odd to even). Such a parity change will be effected through the mutual orbital angular momenta l_1 and l_2, which will have values such that

$$|l_1-l_2| = 1,3,5,\text{----}$$

The entrance channel spin s_1 has any value out of

$\frac{5}{2}^-$, $\frac{3}{2}^-$ and $\frac{1}{2}^-$ while the exit channel spin is $\frac{1}{2}^+$. Trying various assortments of values of s_1, l_1 and l_2 yields the following combinations:

for $l_1=0, l_2=1$

$l_1=1, l_2=0,2,4$

$l_1=2, l_2=1,3,5.$

and so on.

A further limitation on the allowed values of l_1 and l_2 is placed by the nature of the observed angular distributions of the reaction products. If the data are fitted with a power series in even powers of $\cos\theta$ [interference terms in odd powers of $\cos\theta$ may enter if the compound state is a mixture of levels of opposite parity and if the incoming and outgoing particle waves contain mixtures of opposite parity, e.g. in the $Li^7(d,n)Be^8$ reaction] of the form $A+B\cos^2\theta + C\cos^4\theta + - - - -$, where θ is the angle between the directions of a and b in the centre-of-mass coordinates, the highest power term $\cos^n\theta$ required indicates that

$l_1 \geqslant \frac{n}{2}$, $I_o \geqslant \frac{n}{2}$ and $l_2 \geqslant \frac{n}{2}$ (Evans, 1955).

The angular distribution can therefore help infer the angular momentum and parity of an energy level, besides indicating the mechanism of the reaction.

X ANGULAR DISTRIBUTION OF THE NEUTRONS CORRESPONDING TO THE GROUND STATE OF Be^8

In the general case of a collision there is an incident particle of mass M_1 and a struck particle of mass M_2, the latter being initially stationary in the laboratory coordinates. The motion of the particles is easily derived from laws of conservation of energy and momentum before and after the collision, if it is assumed that mass $M_1 \ll M_2$, so that the struck particle remains at rest throughout the collision. In most impacts M_1 is not negligible in comparison to M_2. In such cases it is convenient to consider the collision in a coordinate system whose origin is at rest at the centre of mass of the colliding particles. Such a set of coordinates is called the centre-of-mass coordinates or C coordinates. The other set whose origin is at rest in the laboratory is called the laboratory coordinates or L coordinates. The relationships between L and C coordinates can be derived from the conservation laws and are independent of the nature of the forces.

In the case of a non-relativistic interaction in which M_1, M_2, M_3 and M_4 denote the incident particle, the struck nucleus, the emitted (observed) particle and the residual nucleus respectively, it can be shown that

$$\text{Sin}\ (\Theta - \theta) = \gamma\ \text{Sin}\ \theta \qquad (10.1)$$

where, Θ = angle of emission of M_3, with respect to the bombarding beam, in C coordinates, θ = angle of emission of M_3 in L coordinates,

and γ = $\frac{\text{velocity of centre of mass in L coordinates}}{\text{velocity of } M_3 \text{ in C coordinates.}}$

In terms of the incident kinetic energy in C coordinates, $T_o = \frac{E_1 M_2}{M_1+M_2}$, γ is given by

$$\gamma = \left[\frac{M_1 M_3}{M_2 M_4} \cdot \frac{T_o}{T_o + Q} \right]^{\frac{1}{2}} \qquad (10.2)$$

Here E_1 is the energy of the bombarding particle and Q is the disintegration energy of the reaction, in L coordinates. Since Q is the change in the total rest mass and also the change in the total kinetic energy, it must have the same value in the laboratory coordinates as it has in the centre-of-mass coordinates.

As the solid ahgle subtended by the detector is different in the two sets of coordinates, the observed relative intensities in the L coordinates must be multiplied by a factor $n(\Theta)$ for conversion into yield in the C coordinates. $n(\Theta)$ is given by

$$n(\Theta) = \frac{\sin \theta \, d\theta}{\sin \Theta \, d\Theta}$$

$$= \frac{\sin^2 \theta}{\sin^2 \Theta} \cos(\Theta - \theta) \qquad (10.3)$$

according to the well known transformation formula (Haxby et al.,1939). The last substitution arises from differentiating (10.1.) with respect to Θ, and solving for $\frac{d\theta}{d\Theta}$.

The above procedure was followed to transfer the observed angular distribution of the $Li^7(d,n)Be^8$ reaction

to the centre-of-mass system, Be^8 being formed in the ground state.

For the present experiment $E_1 = 0.594$ Mev which gives an incident kinetic energy in C coordinates of $T_0 = 0.462$ Mev. From (10.2.), $\gamma = 0.0329$.

The angles of emission of the neutrons and the yield in the two sets of coordinates are shown in table 6.

Table 6

1	2	3	4	5	6
θ	Θ	Yield in L Coordinates	$n(\theta)$	Yield in C coordinates	$Y(\Theta)$
0^o	0^o	2.488	1.000	2.488	1.00
45^o	46.4^o	1.975	0.954	1.884	0.76 ± 0.07
90^o	91.95^o	1.609	1.001	1.610	0.65 ± 0.06
135^o	136.4^o	1.386	1.050	1.455	0.58 ± 0.06

The yields shown in column 3 were derived from the number of tracks and the corresponding volume of emulsion scanned, and have been entered in table 6, for the different plates, in terms of number of tracks observed per 10^8 micron^3. In the last column, the yields in the C coordinates are tabulated as $Y(\Theta)$, the values being normalised to 1.00 for $\Theta = 0$. The probable error in the observations is indicated.

The results are shown in fig. 8. The angular distribution of the neutrons, corresponding to the formation of Be^8 in the ground state, in the centre-of-mass system shows a maximum in the forward direction.

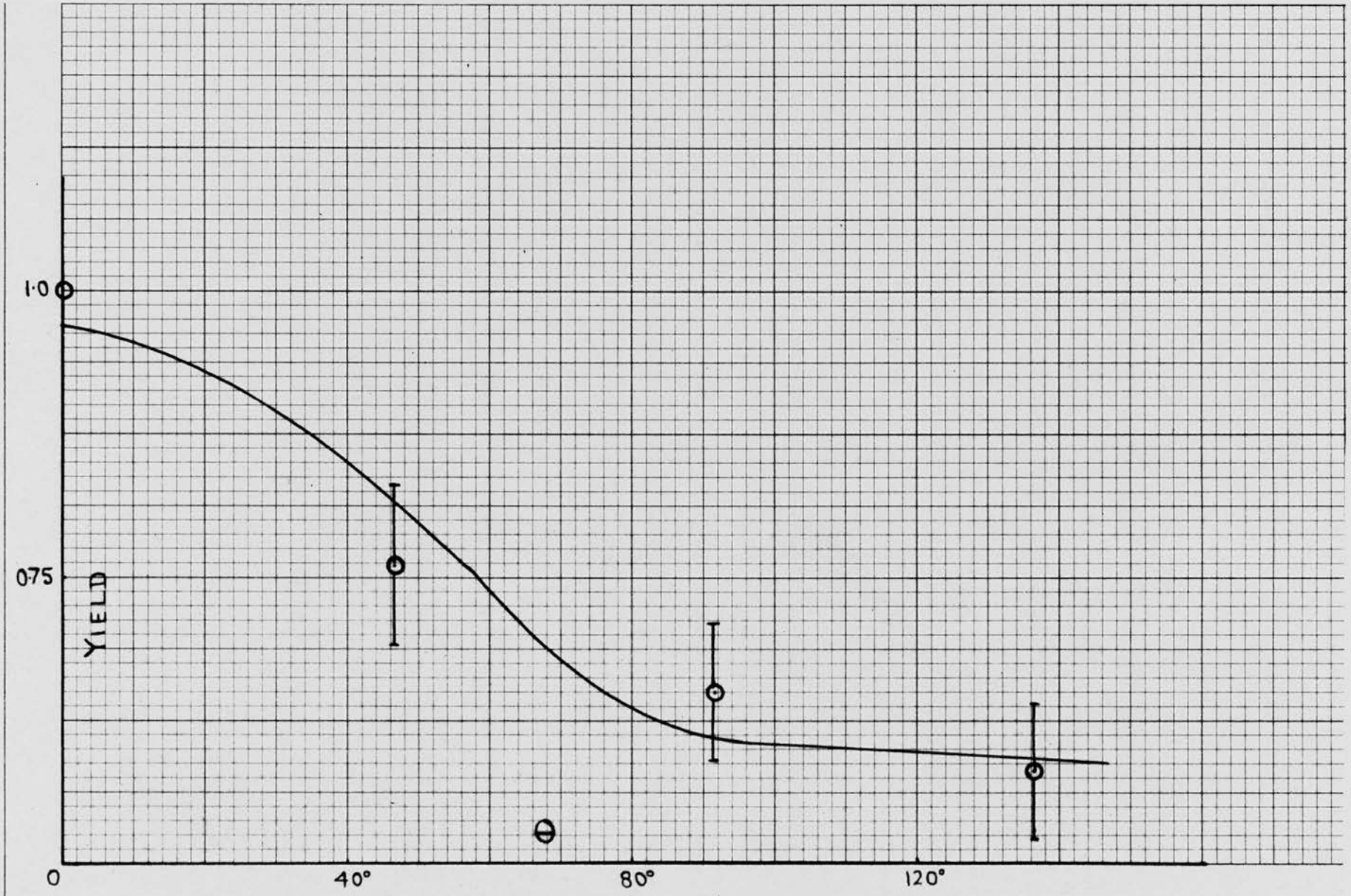


FIG. 8. ANGULAR DISTRIBUTION IN THE CENTER-OF-MASS SYSTEM OF THE REACTION $Li^7(d,n)Be^8$

The yield decreases as the angle of observation with respect to the bombarding beam increases.

These results differ appreciably from those reported by Trumpy et al. (1952,1953). Their angular distribution in the C-coordinates showed an increasing yield from the forward direction towards the backward angles attaining a maximum value at 121.7° and then decreasing again. As these authors were operating on a resonance, the reaction may be expected to proceed to a considerable extent through the compound nucleus mechanism. In the present work, as the deuteron energy was a little below the 0.7 Mev resonance, some contributions from stripping are also likely. This is borne out by the observation of Trumpy et al. that at a deuteron energy lying between the resonances a small relative intensity was obtained in the backward direction.

To have an approximate idea of the relative importance of the stripping process and the compound nucleus formation in the present experiment, the angular distribution in the centre-of-mass system, (table 6) was fitted with a simple power series of the form

$$Y(\theta) = A + B \cos\theta + C \cos^2\theta \quad \text{(see sec. IX.2)}$$

Following the method of least squares, the following polynomial was found to give the best fit:

$$Y(\theta) = 0.615 + 0.162 \cos\theta + 0.188 \cos^2\theta \qquad (10.4)$$

The yields at the different angles calculated according to (10.4) are shown below along with the

curves

corresponding observed values, and shown by the thick curve in Fig. 8.

θ	Observed yield	Calculated yield
0°	1.00	0.97
46.4°	0.76 ± 0.07	0.82
91.95°	0.65 ± 0.06	0.61
136.4°	0.58 ± 0.06	0.59

The difference between $Y(\theta)$ observed and calculated, lies within the range of probable error involved.

It can be said that this angular distribution is adequately described by compound nucleus terms alone, since no stripping term has been needed. This indicates that the formation of Be^{8} in the ground state takes place entirely through the compound nucleus mechanism. As pointed out later (see sec. XII) the present data is insufficient to draw such a definite conclusion.

XI THE LOWER NEUTRON ENERGY SPECTRA

At the angles of observation of 0° and 135° with respect to the direction of the deuteron beam, in the early stages of microscopic examination, measurements had been made on all recoil proton tracks that fulfilled the following conditions:

a). the angle $\beta \leqslant 5^\circ$

b). the depth angle $\theta \leqslant 3^\circ$ for the track of a proton travelling towards the surface of the emulsion and $\leqslant 7^\circ$ for one moving towards the bottom of the plate. (see sec. I.7. and IV.1.).

All tracks whose lengths exceeded about nine microns were considered. For those shorter still, the depth angle could not be ascertained with any accuracy and they were consequently left out. Some tracks of lengths shorter than $\sim$ 18 microns might not have been counted due to inaccuracy in the depth determination across short projected distances, while estimating the angle θ. Therefore there will be a region of lost tracks at the lowest energy end of the neutron spectrum. Such a region extends up to about 1.1 Mev in fig. (9a) and (10a), in which the data for each angle have been collected in the form of a histogram with the number of tracks plotted against the neutron energy, in intervals of 0.1 Mev.

At the 0° angle out of a total of 2000, 1417 recoil protons were observed with energies $\leqslant 4.95$ Mev; the similar number at 135° being 732, out of 1000, with

energies $\leqslant$ 4.0 Mev. The upper limits of neutron energies of 4.95 and 4.0 Mev, respectively, at the two angles of observation corresponded to an excitation of Be^8 of 11.06 Mev.

As the lithium target was 100% Li^7, there could be no group of neutrons in this region, resulting from the $Li^6 + D^2$ reaction. There may however be a neutron group due to the reaction

$$D^2 + D^2 \longrightarrow He^3 + n^1 \qquad (11.1)$$

with a Q value of 3.265 Mev. (Van Patter and Whaling: 1954). The position of such a group will be at neutron energies of about 3.69 and 2.04 Mev, respectively, at the 0^o and 135^o angles. These were calculated from the relation (see appendix II),

$$E_n^{\frac{1}{2}} = 0.354 \cos\theta\, E_d^{\frac{1}{2}} + (0.749Q + 0.249E_d + 0.125 \cos^2\theta\, E_d)^{\frac{1}{2}}$$

The observed distribution of neutron energies (fig. 9a and 10a) was corrected for variation of neutron-proton cross-section for energy (Adair, 1950). To reduce the effect of statistical fluctuations a strong smoothing was applied by using the Spencer 21-term formula. The smoothed spectra thus obtained are shown as curve I in fig (9b) and (10b) at the two angles. Curve II in these figures shows the extension to the lower energy side, of the neutron group corresponding to the wide 10 Mev level in Be^8, as observed in the higher energy spectra (fig.7).

The curve III (fig. 9b and 10b) obtained on subtracting

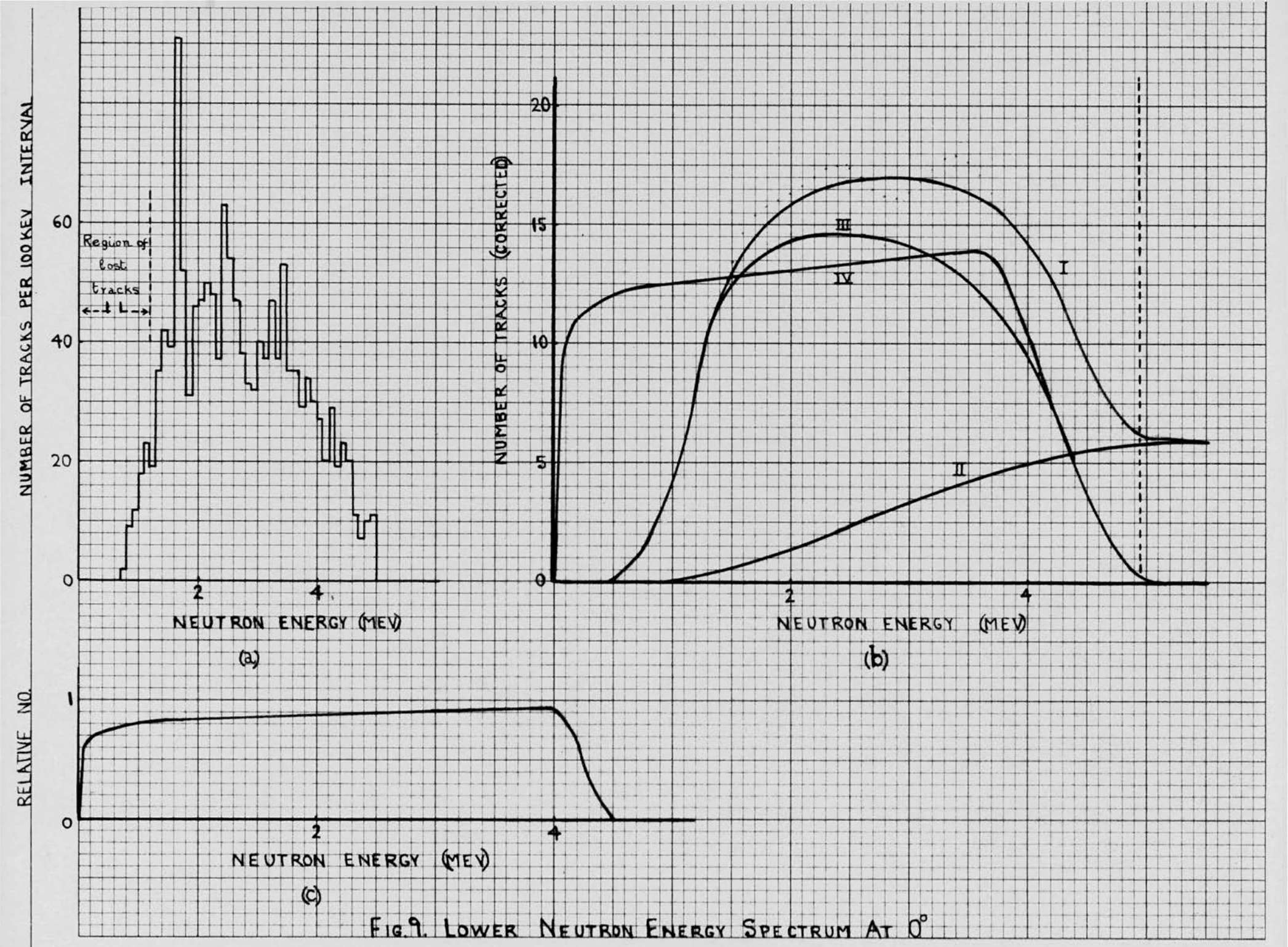


FIG. 9. LOWER NEUTRON ENERGY SPECTRUM AT 0°

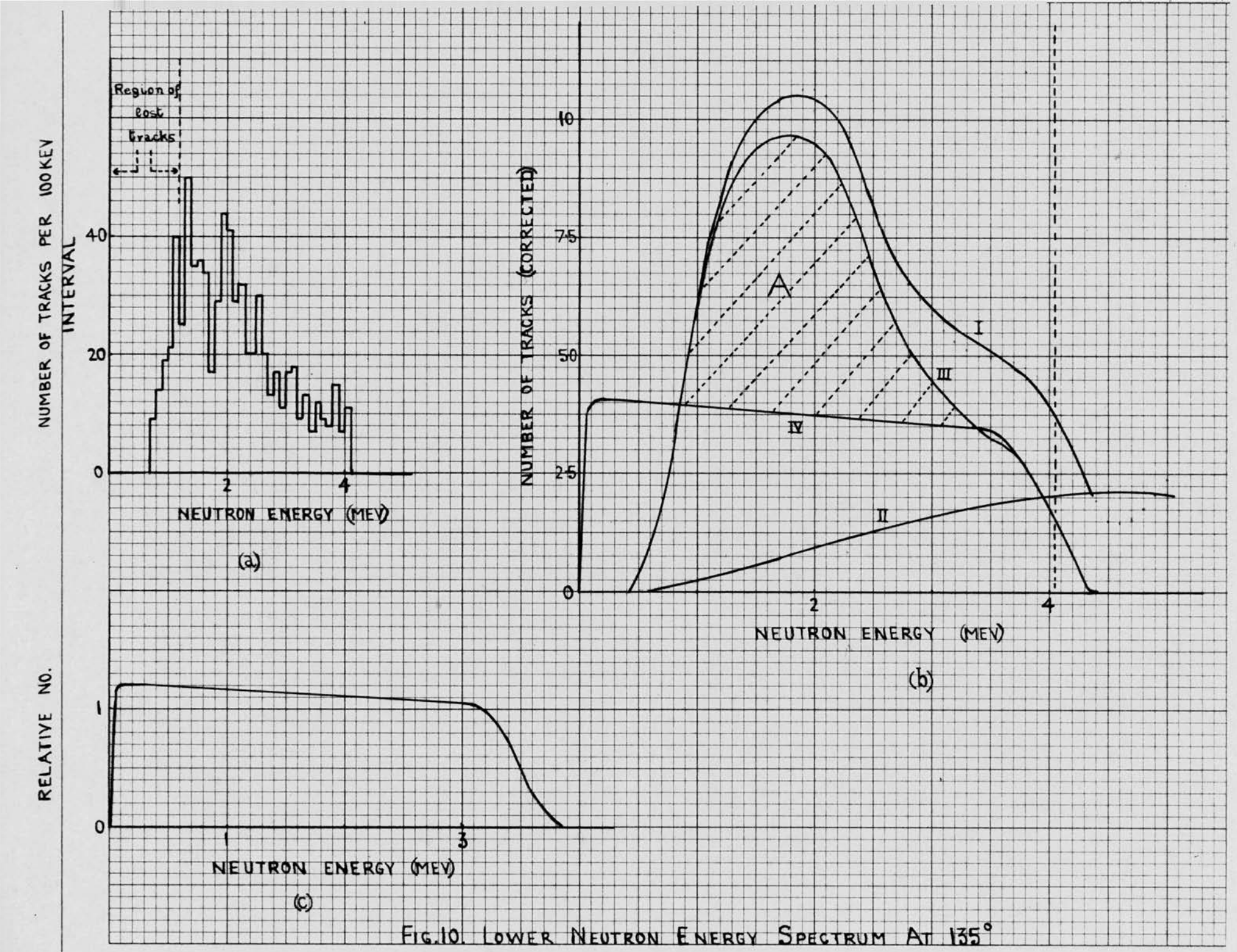


FIG. 10. LOWER NEUTRON ENERGY SPECTRUM AT 135°

the neutron group II from the observed true distribution I, will include the neutrons emitted according to the following modes of the $Li^7 + D^2$ reaction:

$$Li^7+D^2 \longrightarrow Be^{9*} \longrightarrow \begin{cases} He^5+He^4;\ He^5 \longrightarrow He^4+n^1 & (11.2) \\ Be^8 + n^1 & (11.3) \\ He^4+He^4+n^1 & (11.4) \end{cases}$$

and also from the D-D reaction (11.1).

For the reason mentioned earlier (see sec. I and VIII) the contribution of the direct three particle break up (11.4) may be treated as negligible. The mode (11.2) in which He^5 is formed in the intermediate stage may be considered to be much more probable in comparison.

XI.1. The He^5 break up.

According to Bethe (1937) for a two-stage process like

$$Li^7 + D^2 \longrightarrow He^5 + He^4 + Q_1$$
$$He^5 \longrightarrow He^4 + n^1 + Q_2,$$

E_4', the energy of the neutron in the C-coordinates varies between the following limits:

$$\frac{1}{M_3}\left[(E_3'M_4)^{\frac{1}{2}} - (Q_2M_5)^{\frac{1}{2}}\right]^2 < E_4' < \frac{1}{M_3}\left[(E_3'M_4)^{\frac{1}{2}} + (Q_2M_5)^{\frac{1}{2}}\right]^2 \quad (11.5)$$

The indices 0,1,2 and 3 refer to the particles Li^7, D^2, He^4 and He^5, respectively, in the first stage of the reaction, indices 4 and 5 to the final product nuclei n^1 and He^4. Q_1 is the energy evolution in the first part of the reaction and Q_2 the energy given off in the break up of the He^5 nucleus. M_i denotes the mass and E_i, E_i'

the energies of the particle i in the L- and C- coordinates, respectively.

That the distribution of values of E'_4 within the limits indicated in (11.5) is uniform, rests on the condition that the break up of He^5 is isotropic in the centre-of-mass system.

Riviere and Treacy (1957) studied the alpha-spectrum from the deuteron bombardment of Li^7 and have reported that the angular distribution of the α-particles contributing to the formation of He^5 in reaction (11.2) is isotropic at a deuteron energy of 900 Kev, to within an experimental error of 2 per cent. In an earlier publication French and Treacy (1951) had concluded from observations on coincidence between the successive α-particles of the same process, that the He^5 break up was not isotropic in the centre-of-mass system, also mentioning that the results on the angular correlation were not accurate enough.

It may therefore be reasonably assumed that the neutrons from the He^5 break up will have a rectangular distribution in the C-coordinates. On this basis making use of Bethe's relation (11.5) for two stage disintegrations, the energy distribution of the neutrons in the laboratory coordinates can be obtained.

For the deuteron energy used in this experiment, the limits of E'_4 were calculated to be 0.12 and 3.78 Mev. On

the considerations mentioned above, the distribution of values of E_4' in this range was taken to be uniform. This energy range for E_4' was divided into six equal intervals and the corresponding values of neutron energy E_4 in the laboratory coordinates calculated. For the latter energy intervals thus obtained, the line shape of the energy distribution of the neutrons in the laboratory was worked out. This is shown in fig. (9c) and (10c) for the angles of 0° and 135°, respectively, the ordinates being marked on an arbitrary scale. The neutron energies E_4 lie between the limits of 0.11 to 4.24 Mev and 0.10 to 3.43 Mev, respectively.

This line shape for the neutron emission from the break up of He^5 was then used to estimate the contribution of the mode (11.2) in which He^5 is the intermediate product.

XI.2. Discussion.

The neutron spectrum at the 135° angle (fig.10b) can be interpreted as follows:

The curve III represents the neutrons emitted according to processes (11.2) and (11.3), and possibly, to a certain extent, from the D-D reaction (11.1). The sudden rise in the number of neutrons at about 4 Mev can be taken as indication of the high energy-end of the neutron group from process (11.2). Fitting at this point the line shape of the neutron yield from He^5 break up (fig.10c), the curve IV was obtained. The neutrons of energy less

than about 1.1 Mev did not figure in the measurements, as they belonged to the region of lost tracks. The shaded region A (fig.10b) shows the combined number of neutrons arising from the D-D reaction plus those corresponding to a possible level in Be^8.

From the curves III and IV and from the known number of tracks in the rest of the spectrum for higher neutron energies, the proportion of neutrons from the decay of Be^{9*} through He^5 formation was estimated. Taking all the data, corrected for variation of the n-p cross-section with energy, the following values were obtained:

The number of neutrons with energy > 4 Mev = 225.

The number of neutrons with energy $\leqslant 4$ Mev = 244.

The number of neutrons with energy $\leqslant 4$ Mev and belonging to the 10 Mev level in Be^8 = 36.

The number of neutrons from He^5 break up, including 31 in the region of lost tracks = 154.

Therefore the proportion of decay of Be^{9*} through He^5 formation

$$= \frac{154}{225+244+31} = \frac{154}{500} \text{ , i.e. about 31\%;}$$

so that 31% of all the disintegrations observed were through process (11.2).

It is not possible to make a similar fit to the curve III (fig. 9b) for the 0^o angle, probably because the D-D peak and the rise in the number of neutrons from the He^5 break up overlap. The maximum possible proportion of decay through process (11.2) can however be estimated by assuming that all the observed neutrons in the low

energy region ($E < 4.95$ Mev) resulted through He^5 formation and none through the other processes (11.1) and (11.3). The line shape of fig. (9c) when fitted to curve III (fig. 9b) yielded the curve IV for the neutron distribution through He^5 break up.

The following data, corrected for variation of n-p cross-section with energy, were obtained.

The number of neutrons with energy > 4.95 Mev = 585

The number of neutrons with energy $\leqslant 4.95$ Mev = 555

The number of neutrons with energy $\leqslant 4.95_8$ Mev and belonging to the 10 Mev level in Be^8 = 62

The number of neutrons from He^5 break up which fell in the region of lost tracks = 60

Hence the maximum proportion of decay of Be^{9*} through He^5 formation

$$= \frac{555-62+60}{585+555+60} = \frac{553}{1200}, \text{ i.e. about } 46\%;$$

so that the maximum possible contribution of reaction (11.2) to the total disintegrations observed came to about 46%.

A similar calculation was made for the data at the 135° angle. Ignoring the processes (11.1) and (11.3) and assuming all the neutrons in the lower energy region to be produced through He^5 break up, the maximum possible proportion of decay of Be^{9*} through channel (11.2) came to about 50%.

These quantitative results were compared with those of Riviere (1956) who observed the coincidences between

successive alpha-particles from the reaction $Li^7(d,\alpha)He^5(n)He^4$ at a deuteron energy of 900 Kev using two proportional counters. In the 6.78 to 8.2 Mev alpha-particle energy range investigated, Riviere was able to observe α-particles from all excitations of Be^8 between 9.5 and 15.7 Mev. From the energy distributions he concluded that in the region studied, the decay of Be^{9*} through a three-body break up and through formation of Be^{8*} contributed less than one-tenth of the disintegrations observed, or in other words, more than 90% of the decay took place through the formation and subsequent break up of He^5.

It was noticed that Riviere had omitted the greater part of the present spectrum. The relative proportions for the region investigated by Riviere, came out as follows in the present experiment.

(i) At the 0^o angle.

The 9.5 Mev excitation of Be^8 corresponded to a neutron energy of 5.9 Mev.

The total number of observed neutrons with energy ~~of~~ $\leqslant$ 5.9 Mev = 585

From the data given earlier for this angle, the maximum possible proportion of disintegrations through He^5 formation

$$= \frac{553}{585+60} = \frac{553}{645} \quad \text{i.e. about } 86\%$$

(ii) At the 135^o angle.

The 9.5 Mev excitation level of Be^8 corresponded

to a neutron energy of 4.9 Mev.

The total number of observed neutrons with energy $\leqslant$ 4.9 Mev = 262

The number of neutrons with energy $\leqslant$ 4.9Mev and belonging to the 10 Mev level in Be^8 = 54

The number of neutrons from He^5 break up which fell in the region of lost tracks = 55

Therefore the maximum possible proportion of Be^{9*} decay through channel (11.2)

$$= \frac{262-54+55}{262+55} = \frac{263}{317}, \text{ i.e. about } 83\%$$

Although it is noticed that more than 80% of the disintegrations may take place through formation of He^5, this is the maximum possible proportion. The actual proportion will be lesser, depending on the contributions from other reactions (11.1) and (11.3). From the conclusions of Riviere that more than 90% of the decay of Be^{9*} takes place through process (11.2), it seems that the probability of this mode of the reaction, in which He^5 is the intermediate product, increases with the increase in excitation energy.

XI.3. Conclusion

The $Li^7 + D^2$ reaction results in the formation of the compound nucleus Be^{9*} which can disintegrate according to either of the three competing channels:

(a) a direct three particle break up.

(b) through formation of He^5 as an intermediate product which subsequently breaks up into He^4 plus a neutron.

(c) through formation of Be^8 emitting a neutron.

Treating the contribution of mode (a) as negligible, the probable proportion of decay through mode (b) comes to about 31% with a maximum value of about 50%. Therefore at least half of the neutrons observed are produced along with Be^8, the latter may be formed in the ground state or in any of the excited states.

From the comparison of these results with those of Riviere (1956) for the small portion of the neutron spectrum studied by him, it seems that the mode of this reaction through the formation of He^5, becomes more probable at higher energies of excitation.

XII CONCLUSIONS

Evidence has been found for only three levels in Be^8 below 12 Mev excitation. These, namely the ground state and those at 2.9 and 10.4 Mev excitation, are the three rotational states in Be^8.

Although the angular distribution of neutrons, corresponding to the formation of Be^8 in the ground state, points to the deduction that the $Li^7(d,n)Be^8$ reaction takes place according to the compound nucleus formation, the evidence is not sufficient enough. It has been possible to make measurements on plates at only four angles. The plates exposed at other intermediate angles remain to be scanned. Definite conclusions regarding the mechanism of this reaction can be derived only when data at, at least three or four more angles become available. It is just possible that at other intermediate angles the observed yield may deviate markedly from that calculated with the help of compound nucleus terms alone and a polynomial in $\cos\theta$ plus a Butler stripping function, $B_\ell(\theta)$, may be needed to provide a better fit. At the deuteron energy used in the present experiment, which lies near the first resonance, it seems that both the compound nucleus and stripping mechanisms contribute to the angular distribution, the former being the more important of the two.

On the assumption that direct three-particle disintegrations are less probable as compared to two-stage

processes, it has been found that between 30-50% of the observed disintegrations take place by way of formation of He^5 in the intermediate stage, which subsequently break up emitting a neutron. The observations are [redacted] complementary to [redacted] the results of Riviere (1956). It seems that the mode of this reaction, through He^5 formation, becomes more probable at higher excitation energies. It may be inferred that at least half of the total disintegrations observed correspond to formation of Be^8 in the ground or any of the excited states.

Criteria have been set for analysing the experimental data in regard of possible statistical fluctuations. More measurements have to be made on the plates already scanned, in order to improve the statistics, and on the plates at other angles. It is intended to continue this work to obtain more information about the energy levels in Be^8 and on the mechanism of the $Li^7(d,n)Be^8$ reaction.

APPENDIX I

The angle of dip

While scanning the plates different criteria were set, regarding the angle of acceptance θ between the track and its projection on the emulsion plane, for recoil protons travelling towards the top and bottom surfaces of the emulsion (see sec. IV.1.). This difference occurred due to the 2° angle of inclination of the plates with the neutron direction during irradiation. [Although the directions of the neutrons incident on various parts of any plate are different, the change in direction in the vertical plane amounts to $< 0.5^{\circ}$, so that the neutron direction can be taken to be parallel to the angle defining mark against which the plate was held at the time of exposure].

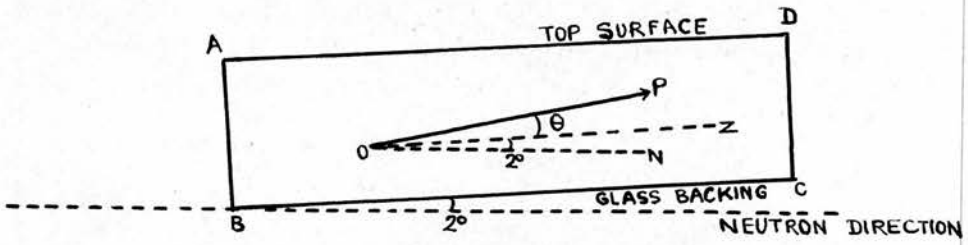


FIG. 11

In fig. 11 is shown a section of the plate in a plane at right angles to the surface of the emulsion (mentioned above as the vertical plane), AB being the thickness. Let a recoil proton start its journey at the point O and travel towards the top surface in the plane passing through OP. Also let ON and OZ, respectively represent the planes parallel to the incident neutron direction and the

emulsion surface.

Then $\hat{ZON} = 2^{o}$. The observed angle θ between the track and its projection on the emulsion plane is $\hat{POZ}$. From the fig. it is seen that the angle α, the so called "angle of dip", which the track subtends with the neutron direction is $\theta + 2^{o}$.

It can be similarly shown that for a recoil proton travelling towards the bottom of the emulsion $\alpha = \theta - 2^{o}$.

APPENDIX II

Derivation of the reaction formula

By consideration of the simple dynamics of a collision between a nucleus A and a deuteron D, giving rise to a product nucleus B and a neutron N, with an energy release Q, a simple relation can be derived between the nuclear disintegration energy Q, and deuteron and neutron energies as measured in laboratory coordinates.

Let the masses of the reacting particles A, D, B and N be respectively M_2, M_1, M_4, M_3 and their energies E_2, E_d, E_4, E_n. Let the angles between the direction of emission of the neutron and the initial direction of the deuteron be θ and that between the direction of recoil of the nucleus B and the initial deuteron be ϕ. Since the nucleus A is initially at rest in laboratory space $E_2=0$.

Applying the laws of conservation of energy and momentum, we have

$$E_4 + E_n = E_d + Q \qquad (1)$$

$$(M_4E_4)^{\frac{1}{2}} \cos \phi + (M_3E_n)^{\frac{1}{2}} \cos \theta = (M_1E_d)^{\frac{1}{2}} \qquad (2)$$

$$(M_4E_4)^{\frac{1}{2}} \sin \phi = (M_3E_n)^{\frac{1}{2}} \sin \theta \qquad (3)$$

From equation (3),

$$\cos \phi = \left[1 - \frac{M_3E_n}{M_4E_4} \sin^2\theta \right]^{\frac{1}{2}}$$

Substituting this in equation (2) leads to

$$M_4E_4 = M_1E_d + M_3E_n - 2(M_1M_3E_dE_n)^{\frac{1}{2}} \cos \theta$$

Hence from equation (1), we obtain the general reaction

formula

$$M_4Q = (M_4 + M_3)E_n - (M_4-M_1)E_d - 2(M_1M_3E_dE_n)^{\frac{1}{2}} \cos\theta \quad (4)$$

By substitution of the known mass values (Li et al: 1951) the relations for the different reactions can be obtained.

(1) $\underline{Li^7(d,n)Be^8}$;

$M_1 = 2.01474$ a.m.u.

$M_3 = 1.00898$ a.m.u.

$M_4 = 8.00785$ a.m.u.

Hence,

$$8.008\ Q = 9.017\ E_n - 5.993\ E_d - 2.855(E_dE_n)^{\frac{1}{2}} \cos\theta \quad (5)$$

This equation can be regarded as a quadratic in $(E_n)^{\frac{1}{2}}$.

On rearranging the terms, we have

$$9.017\ E_n - (2.855\ E_d^{\frac{1}{2}} \cos\theta)\ E_n^{\frac{1}{2}} - (8.008\ Q + 5.993\ E_d) = 0 \quad (6)$$

From its general solution, we obtain

$$E_n^{\frac{1}{2}} = 0.158 \cos\theta\ E_d^{\frac{1}{2}} + [0.888Q + 0.665E_d + 0.025 \cos^2\theta\ E_d]^{\frac{1}{2}} \quad (7)$$

(2) $H^2(d,n)\ He^3$;

$M_1 = 2.01474$ a.m.u.

$M_3 = 1.00898$ a.m.u.

$M_4 = 3.01698$ a.m.u.

Hence,

$$Q = 1.334E_n - 0.332E_d - 0.945(E_nE_d)^{\frac{1}{2}} \cos\theta \quad (8)$$

which gives

$$E_n^{\frac{1}{2}} = 0.354 \cos\theta\ E_d^{\frac{1}{2}} + [0.749Q + 0.249E_d + 0.125 \cos^2\theta\ E_d]^{\frac{1}{2}} \quad (9)$$

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